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DEMAND SHIFTING WITH THERMAL MASS IN LARGE COMMERCIAL BUILDINGS: FILED TESTS, SIMULATIONS AND AUDITS

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California Energy Commission
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Prepared By:
Lawrence Berkeley National Laboratory



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**Demand Shifting With Thermal Mass in Large Commercial Buildings:
Field Tests, Simulations and Audits**

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PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to \$62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy Systems Integration

What follows is the final reports for the Demand Shift with Building Thermal Mass Project, 500-03-026 Task 4.2, conducted by the Lawrence Berkeley National Laboratory. The report is entitled “Demand Shifting with Building Mass in Large Commercial Buildings: Field Tests, Simulations and Audits”. This project contributes to the Energy Systems Integration Program.

For more information on the PIER Program, please visit the Commission's Web site at: <http://www.energy.ca.gov/research/index.html> or contact the Commission's Publications Unit at 916-654-5200.

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EXECUTIVE SUMMARY

The principle of pre-cooling and demand limiting is to pre-cool buildings at night or in the morning during off-peak hours, storing cooling in the building thermal mass and thereby reducing cooling loads during the peak periods. Savings are achieved by reducing on-peak energy and demand charges. The potential for utilizing building thermal mass for load shifting and peak demand reduction has been demonstrated in a number of simulation, laboratory, and field studies.

In Summer 2003, a pre-cooling case study was conducted at the Santa Rosa Federal Building. It was found that a simple demand limiting strategy performed well in this building. This strategy involved maintaining zone temperatures at the lower end of the comfort range (70°F) during the occupied hours before the peak period and floating the zone temperatures up to the high end of the comfort range (78°F) during the peak period. With this strategy, the chiller power was reduced by 80 to 100% (1 to 2.3 W/ft²) during peak hours from 2 pm to 5 pm without having any thermal comfort complaints submitted to the operations staff.

Although the initial study was quite successful, some key questions remained unanswered, including: What was the actual comfort reaction? What is the effect of extended (nighttime) pre-cooling on the following day peak shed? What will happen in really hot weather?

In order to address these questions, field tests were performed in two buildings in 2004. In addition to further testing at the Santa Rosa Federal Building, tests were performed in a medium size office building in Rancho Cordova (McCuen Center One Building). A key feature of the 2004 study was the comfort survey. A web-based comfort survey instrument was developed and used in the field tests to assess thermal sensation, comfort and productivity ratings in these two buildings. To supplement the field tests, EnergyPlus computer simulation models were built for the two buildings and used to estimate the impact of various pre-cooling strategies on peak demand. In addition, a set of buildings were audited to assess their suitability for pre-cooling in terms of their building materials and control system and the willingness and ability of the building staff to implement pre-cooling strategies. These audits provide a preliminary assessment of customer acceptability and market readiness of pre-cooling.

The results of the comfort surveys in the two test buildings indicate that occupant comfort was maintained in the pre-cooling tests as long as the room temperatures were between 70 and 76°F. Night-time pre-cooling was found to have varying effects on the magnitude of the following day's peak demand, with a number of factors affecting its effectiveness. We found it was important to manage the afternoon load shedding by ramping the zone temperature set-points rather than stepping them up. This can be particularly important on hot days or in buildings with smaller thermal time constants, where air conditioning-related electrical power could "rebound" and exceed the peak demand typically seen under normal operation. Simulation of the various reset strategies demonstrated that the exponential temperature reset strategy for the thermal mass discharge period is the best of all the three thermal mass discharge strategies studied. The simulation results indicate that pre-cooling has a greater impact on reducing air-conditioning-related peak period electrical loads than just raising the zone temperatures during the peak period.

Pre-existing building system problems can impact the effectiveness of pre-cooling. Problems were encountered in the McCuen Center One building where some zones experienced excessively low temperatures during the pre-cooling tests, which resulted in occupant complaints. The low temperatures were due to pre-existing faults in the HVAC system, possibly air balance problems or mis-calibrated temperature sensors, that were exacerbated by the pre-cooling. One conclusion that can be drawn from this experience is that pre-existing comfort problems should be identified and addressed before implementing HVAC-based demand respond strategies. It is also important to commission the HVAC system in order to understand the building before running any demand-shifting control strategies.

Most of the buildings surveyed in the audit process appeared suitable physically and the owners and operators expressed confidence in their ability to implement pre-cooling, though there were consistent reservations about potential comfort problems. In the light of the experience at the building at McCuen Center One, these responses should be treated with caution. A screening tool that is designed to reveal comfort and other control problems would be desirable to reduce the risk of problems and dissatisfied customers.

The conclusion of the work to date is that pre-cooling has the potential to improve the demand responsiveness of commercial buildings while maintaining acceptable comfort conditions. Further work is required to quantify and demonstrate the effectiveness of pre-cooling in different building types and climates and to develop screening tools that can be used to select suitable buildings and customers, identify the most appropriate pre-cooling strategies and estimate the benefits to the customer and the utility.

1. INTRODUCTION

The principle of pre-cooling and demand limiting is to pre-cool buildings at night or in the morning during off-peak hours, storing cooling in the building thermal mass and thereby reducing cooling loads and reducing or shedding related electrical demand during the peak periods. Cost savings are achieved by reducing on-peak energy and demand charges. The potential for utilizing building thermal mass for load shifting and peak demand reduction has been demonstrated in a number of simulation, laboratory, and field studies (Braun 1990, Ruud et al. 1990, Conniff 1991, Andresen and Brandemuehl 1992, Mahajan et al. 1993, Morris et al. 1994, Keeney and Braun 1997, Becker and Paciuk 2002, Xu et al. 2003). This technology appears to have significant potential for demand reduction if applied within an overall demand response program.

The primary goal associated with this research is to develop information and tools necessary to assess the viability of and, where appropriate, implement demand response programs involving building thermal mass in buildings throughout California. The project involves evaluating the technology readiness, overall demand reduction potential, and customer acceptance for different classes of buildings. This information can be used along with estimates of the impact of the strategies on energy use to design appropriate incentives for customers.

This research was conducted as part of the Demand Shift with Building Thermal Mass (DSTM) Project, funded by the California Energy Commission's PIER-funded Demand Response Research Center. The DSTM Project included research of the impacts of demand shifting with thermal mass in small and large commercial buildings. The small commercial buildings research is being conducted by Purdue University, Southern California Edison and University of California Berkeley. The large commercial buildings research discussed in this report was conducted by Lawrence Berkeley National Laboratory and the Center of the Building Environment (CBE) at the University of California Berkeley. The research tasks tackled in this study and their objectives are described below.

1.1 Field Tests at the Two Commercial Buildings

The objective of this field test was to evaluate and demonstrate demand shifting-based demand response (DR) technologies in real buildings. Field testing of demand shifting-based DR control strategies took place at the Santa Rosa Federal Building and the County of Sacramento-occupied McCuen One Building in Ranch Cordova. The Santa Rosa Federal Building testing, continued from Summer 2003, focused on the demand reduction and comfort response resulting from the use of various zone temperature set-point profiles under different weather conditions. An EnergyPlus model of the building was used to evaluate different pre-cooling strategies. Key questions remaining from the 2003 pre-cooling study were:

- Even though there were no complaints to the facility staff, what was the actual occupant comfort reaction?
- What is the effect of extended (nighttime) pre-cooling on the following day's peak demand shed?

- What will happen in really hot weather? Does the temperature rise faster in the afternoon in the cases already studied?
- How well do the simulations predict the observed temperature and demand response?

A custom version of UC Berkeley's occupant survey module was used to assess thermal sensation, comfort, and impact on productivity in the two buildings. Temperature trend log data were used to predict temperature complaints. Temperature complaint records for normal control and demand response control were acquired and used to assess the impact of demand response control on thermal discomfort. The results of the 2004 field tests are presented in Section 2.

1.2 Simulation and Economic Analysis

The objective of the simulation study was to predict the benefits of demand shifting with pre-cooling through simulation and economic analysis. Simulations of two building were developed. EnergyPlus models were built for the two buildings and used to study the peak demand impact of HVAC types, demand shifting control strategies and climate during a critical demand period. The models were also used to identify strategies, predict benefits and design the field tests. The results of the simulation study are presented in Section 3.

1.3 Identify Customer Drivers and Barriers and Select Buildings for Audits

The objective of this task was to understand customer issues regarding the use of building mass for demand shifting. Customers' attitudes to prospective utility demand response programs based on HVAC demanding shifting were investigated through discussions with utility account representatives. Interviews were conducted to assess the expected response of owners of individual commercial buildings. The issues identified in this investigation were used to frame different aspects of the rest of the project. These issues included the magnitude of zone temperature set-point changes, willingness to change control strategies and economic issues such as implementation costs and payback periods.

1.4 Audit Buildings for Ease of Demand Shifting Implementation

Audits were performed in eight large commercial buildings to assess their suitability for pre-cooling, in terms of their building materials and control system characteristics as well as the willingness and ability of the building staff to implement pre-cooling. The buildings were selected in consultation with PG&E and SMUD. The building types considered were predominately owner-occupied and included public sector offices, department stores, large discount stores, hotels, hospitals and libraries. The building audit procedure is described in Appendix I and the results are presented in Appendix II.

2. PRE-COOLING FIELD STUDY

2.1 Introduction

In the late summer of 2003, an initial pre-cooling case study was conducted in Santa Rosa Federal building. The objective of this previous study was to demonstrate the potential for reducing peak-period electrical demand in moderate-weight commercial buildings by modifying the HVAC system controls. HVAC performance data and zone temperatures were recorded using the building control system. For the purpose of this study, additional operative temperature sensors for selected zones and power meters for the chillers and the AHU fans were installed. An energy performance baseline was constructed from data collected during normal building operation. Two strategies for demand shifting using the building thermal mass were then programmed into the control system and implemented progressively over a period of one month.

It was found that a simple demand limiting strategy performed well in this building. This strategy involved maintaining zone temperatures at the lower end of the comfort range (70°F) during the occupied hours until 2 pm. Starting at 2 pm, the zone temperatures were allowed to float to the high end of the comfort range (78°F). With this strategy, the chiller power was reduced by 80 to 100% (1 to 2.3 W/ft²) during normal peak hours from 2 pm to 5 pm, without having any thermal comfort complaints submitted to the operations staff. The building thermal mass was effective in limiting the variations in the zone temperature. The average rate of zone temperature change was about one degree per hour. In the worst case zone, the temperature rise was approximately two degrees per hour. An example of the test results from this previous study is shown in Figure 2.1.

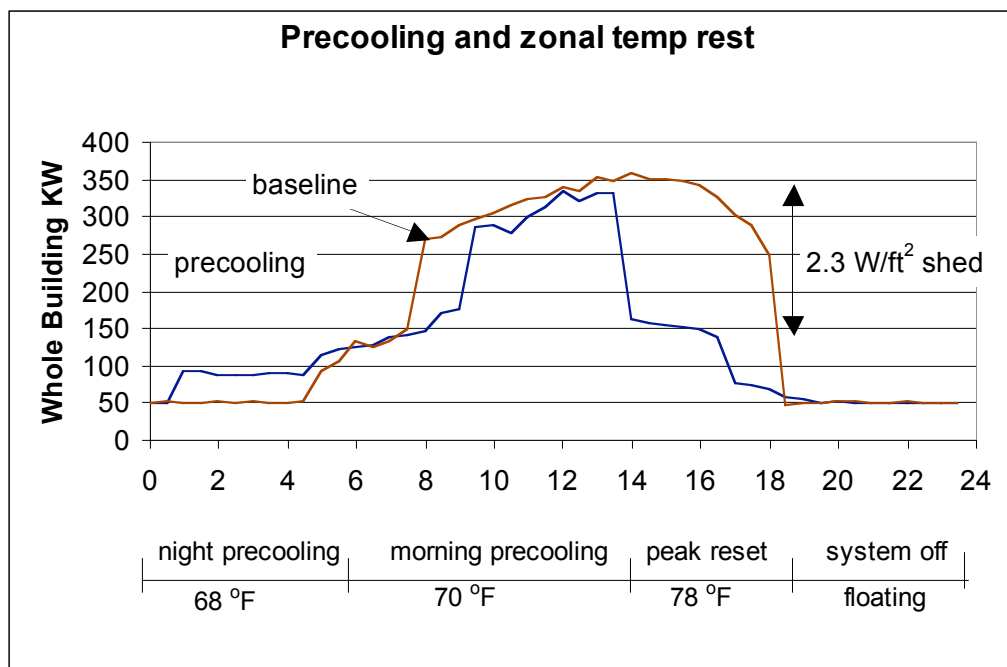


Figure 2.1 Pre-cooling test results in Santa Rosa Federal Building, 2003

Although the initial study was quite successful, some key questions remain unanswered:

- What was the actual comfort response? Even though the occupants in this study made no complaints, further work should include comfort surveys to determine the extent to which thermal discomfort, as a result of different degrees of demand shifting, is not severe enough to cause complaint calls to building operators.
- What is the effect of extended (nighttime) pre-cooling on the following day's peak shed? Although the peak load was reduced significantly in all of the tests, the benefits of nocturnal pre-cooling were unclear. There was insufficient evidence to demonstrate that the extended pre-cooling had any significant effect on the peak demand. This might be because the pre-cooling tests were only performed for one or two days at a time. Longer periods are required for a steady-periodic condition to be obtained than were available for these tests. It may well be that the extended pre-cooling strategies need to be operational for more than a week to see any effects.
- What will happen in really hot weather? Does the temperature rise faster in the afternoon than in the cases that were studied? The maximum outside air temperature during the test period was 88°F, which is significantly lower than ASHRAE's 2.5% cooling design temperature of 95°F (ASHRAE 2005).

2.2 Methodology

In order to address the questions listed above, field tests were scaled up to two buildings in 2004. In addition to the Santa Rosa Federal Building, the County of Sacramento-occupied McCuen Center One Building in Rancho Cordova was selected for testing from the eight buildings audited (see Appendix I). The selection was based on locations, technical feasibility, and owner intentions. A strategy similar to the demand-shifting strategy implemented in 2003, based on zone temperature reset, was used in both buildings.

There were several reasons for picking the McCuen One building as the second test site. First, it is located inland, which would provide more opportunities to test pre-cooling strategies in hot weather. Second, the building has different mechanical system types than the Santa Rosa building. It has two single duct rooftop package units. Third, as with many commercial buildings, this building is leased to tenants instead of being owner occupied. Although this adds more complexity to the field testing, it can shed some light on management issues that need to be tackled before the strategies can be more broadly adopted. Fourth, the building owner and property management team are innovative and they are interested in trying new ideas and methods to reduce their utility costs. A more detailed building description can be found in Section 3 of this report.

One key feature of the 2004 study is the comfort survey. The Center for the Built Environment (CBE) at the University of California Berkeley has developed a web-based occupant indoor environmental quality survey which has been conducted in more than 170 office buildings across North America and Europe. A customized

comfort survey instrument was developed by CBE to assess thermal sensation, comfort and productivity ratings in these two buildings (See Figure 2.2).

Please answer the following questions based on your experience right now:

How would you rate the current temperature in your workspace?

- ☐ Much too warm
- ☐ Too warm
- ☐ Comfortably warm
- ☐ Comfortable (and neither cool nor warm)
- ☐ Comfortably cool
- ☐ Too cool
- ☐ Much too cool

Does the current temperature in your workspace enhance or interfere with your ability to get your job done?

Enhances ☐ ☐ ☐ ☐ ☐ ☐ ☐ Interferes

Any additional comments or recommendations about the current temperature?

Figure 2.2 Web-based comfort survey questions

The web-based comfort survey is short (three pages) and requires less than one minute of the building occupant's time. On the first page, the users were informed about the purposes of the survey, that it is voluntary, confidential and anonymous, and how long it should take to finish. On the second page, the users were asked to fill in their room and phone number to identify their locations in the building for later analysis with temperature logs. Two questions were asked on the third page (Figure 2.2) – one question employs the Bedford scale to assess sensation and comfort, and the other polls the respondents for their opinion on the effect of the current temperature on their productivity. It should be noted that both questions are self-assessment questions instead of being objective questions based on physical measurements. Both questions use seven-point scales for the users' responses.

Contact was made with the building owner and the facility manager to obtain a master e-mail list of the building occupants. This list allowed direct occupant contact to be made in a timely fashion. Initially, the owners and facility managers were reluctant to provide this information because they did not want to have the occupants disturbed. Later, they agreed to release the e-mail address lists when they saw the benefit of understanding their occupants' attitude toward the building thermal environment.

Since indoor temperatures could be different during the mornings and afternoons, the e-mail survey requests were sent twice a day, once in the morning and once in the afternoon. As a first step, an e-mail was sent to all building occupants to explain the purpose of the survey and to ask the recipient to fill out the survey on the days before the pre-cooling tests to construct a baseline. Then during the test days, e-mail requests were sent twice a day to collect the comfort data.

The e-mail letters sent to the occupants are shown in Appendix III and Appendix IV. In all of the e-mails sent to the occupants, no details of the pre-cooling tests were released to them. They were aware that an energy efficiency project was going on in the building, but had no knowledge of the details. This was done deliberately to avoid possible changes in clothing level if they expected a cooler environment in the morning and warmer environment in the afternoon. This was a conservative approach with respect to comfort response. It may well be that occupants would tolerate a wider temperature range if they were informed in advance and had the opportunity to adjust their clothing levels.

2.3 Test Site 1 - Santa Rosa Federal Building

2.3.1 Test Site Description

The Santa Rosa Federal Building is a medium-sized (about 80,000 ft²) governmental office building located in Santa Rosa, California (See Figure 2.3). About half of the space is for offices and half for courtrooms. It has three stories with moderate structural mass, having 6" concrete floors and 4" exterior concrete walls. The office area has a medium furniture density and standard commercial carpet on the floor. The building has a window-to-wall ratio of 0.67, with floor-to-ceiling glazing on the north and south façades and significantly smaller glazing fractions on the east and west. The windows have single-pane tinted glazing. The internal equipment and lighting load are typical for office buildings. There are approximately 100 of occupants in the office area of the building (400 ft²/person).



Figure 2.3. Santa Rosa Federal Building

The building has independent HVAC systems serving the west and east wings. The west wing (office side) has three 75-ton, 30-year old air-cooled chillers. Two dual-duct VAV (variable air volume) air handlers deliver conditioned air to the zones. The east wing has two 60-ton, 10-year old air-cooled chillers with three single duct VAV air handlers. There is one constant-speed water pump for each chiller. All of the chillers have two stage compressors. The supply and return fans for the dual duct system are controlled by variable frequency drives (VFD). The single duct system has constant speed fans with inlet vane controls. There are about 50 zones in the building. The building is fully equipped with digital direct control (DDC), but had no

global zone temperature reset strategies implemented before the study. This strategy was programmed as part of this study.

Operationally, the building is typical of many office buildings. The HVAC system starts at 5 am and pre-heats or pre-cools the building until 8 am. The occupied hours are from 8 am to 5 pm. No major faults in the mechanical system were apparent except for one undersized cooling coil and some air balance problems in the duct system. There are also some minor temperature control problems caused by lack of reheat coils. There are relatively few comfort complaints, averaging about two or three hot or cold calls per month. The building operator has worked at the building for a long time and is quite confident and familiar with the system.

2.3.2 Test Strategies

The two pre-cooling and zone temperature reset strategies that were tested are shown in Figure 2.4. The building was normally operated at a constant set point of 72°F throughout the startup and occupied hours. After 5 pm, the system was shut off and zone temperatures floated. Under normal operation, the set-points in individual zones ranged from 70 to 75°F, with an average value of 72°F. The first strategy tested was termed “pre-cooling + zonal reset”. From 5 am to 2 pm, all the zone temperature set-points were lowered to 70°F. From 2 pm to 5 pm, the set-points were raised to 76°F. After 5 pm, the system was shut off, as in regular operation. The second strategy was termed “extended pre-cooling + zonal reset”. The system was turned on at midnight and the zone temperature set-points were set to 68°F from 12 am to 5 am. The aim was to cool a significant depth of the exposed structural concrete. From 5 am to 2 pm, the set-points were raised to 70°F and, after 2 pm, raised to 76°F. The difference between the two strategies is the extension of the pre-cooling period. One aim of the tests was to determine the effect of the extended pre-cooling on the peak demand shedding.

The temperature reset used in 2004 is more conservative than that used in 2003; the set point in the afternoon was 76°F instead of 78°F previously used. This was not resulting response to comfort complaints, as there were none during the 2003 tests. Rather, the building owner, GSA, requested a more conservative approach.

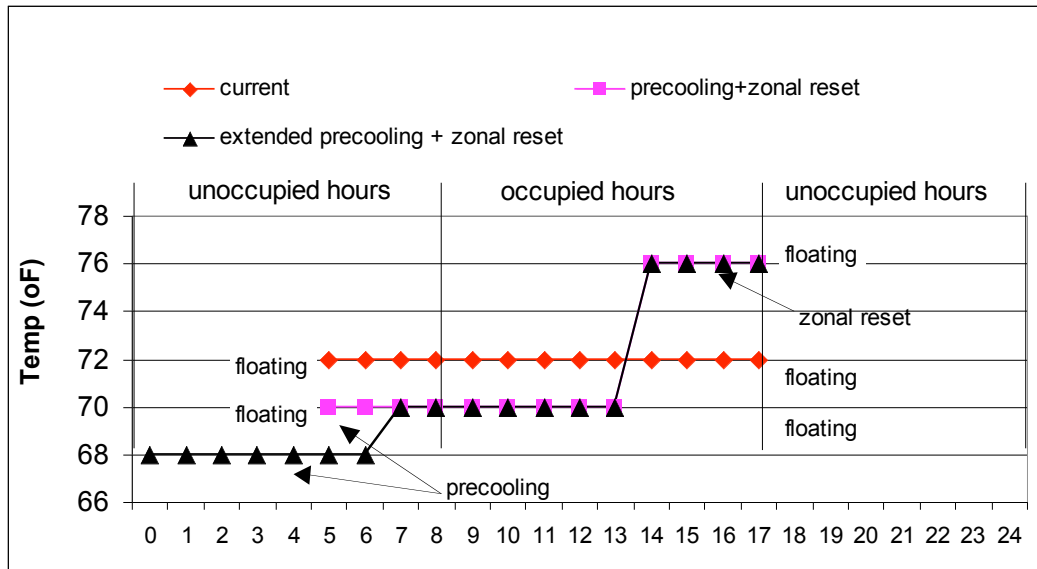


Figure 2.4 Pre-cooling and demand shed strategies (Santa Rosa Federal Building)

2.3.3 Monitoring

The building has a whole building power meter and five permanent chiller power meters. There is a weather station measuring outside air temperature and humidity. The HVAC performance data were recorded using the building control system. Roughly 500 data points were collected at 15-minute intervals. Four temporary fan power meters were installed on the air handling unit fans for this study to determine the impact of control strategies on the air distribution system. Twelve operative temperature sensors were installed in the buildings. The operative temperature sensors consist of temperature sensors enclosed in hollow spheres and measure a weighted average of the radiant temperature and dry bulb air temperature. Because of the radiant effect, the operative temperature is a better indicator of the thermal comfort than the dry bulb air temperature. This was expected to be important in assessing thermal comfort in this study, because the building surfaces should be cooler as a result of the pre-cooling.

2.3.4 Weather and Test Scenarios

In the 2003 study, the expected strong correlation between peak outside temperature and whole building power was observed. Therefore, baseline days for each test day were selected based on similarity of peak outside air temperature.

The tests were conducted on cool and hot days during late September and early October 2004. Cool days are defined as days when the peak outside air temperature was between 72°F and 75°F and hot days are defined as days when the peak outside air temperature was above 95°F. No days with peak outside temperatures between 75°F and 95°F occurred during the period of the tests.

In total, eight tests were conducted in this study, as listed in Table 2.1. Each test lasted for one day. There were eight pre-cooling and zonal reset tests, six of them were on cool days and two of them were on hot days. There were three "extended

pre-cooling + zonal reset tests”. Three of them were on a cool day and one of them was on a hot day. For hot days, both pre-cooling and extended pre-cooling tests were performed to assess the effect of the extended pre-cooling.

Table 2.1. Pre-Cooling and Zonal Reset Test Scenarios

	Pre-cooling + zonal reset	Extended pre-cooling + zonal reset
Cool days	3	3
Hot days	1	1

2.3.5 Results

The test data showed significant peak demand savings for both pre-cooling strategies. Sample results are shown in Figures 2.5 and 2.6. Figure 2.5 shows whole building power results for the pre-cooling + zonal reset tests on the cool days. The power levels for the baseline and test days were similar in the morning. At 2 pm, when the zone temperatures set-points were reset to 76°F, the cooling plant shut off automatically because the cooling demand fell to zero – as a result, the whole building electric load dropped. The cooling plant stayed off until 5 pm except on one test, when the mechanical system was completely shut off. The cooling demand mostly remained at zero because the zone temperatures did not reach the set-point of 76°F. In this particular test, compared with morning pre-cooling, the extended pre-cooling makes little difference on the whole building electricity consumption during the day period. However, the building did consume fan energy during the previous night. The tests results are consistent with the results found in 2003. The results from both 2003 and 2004 indicate that, for this particular building, extended pre-cooling and pre-cooling only in the morning have similar effects on the electricity demand in the afternoon.

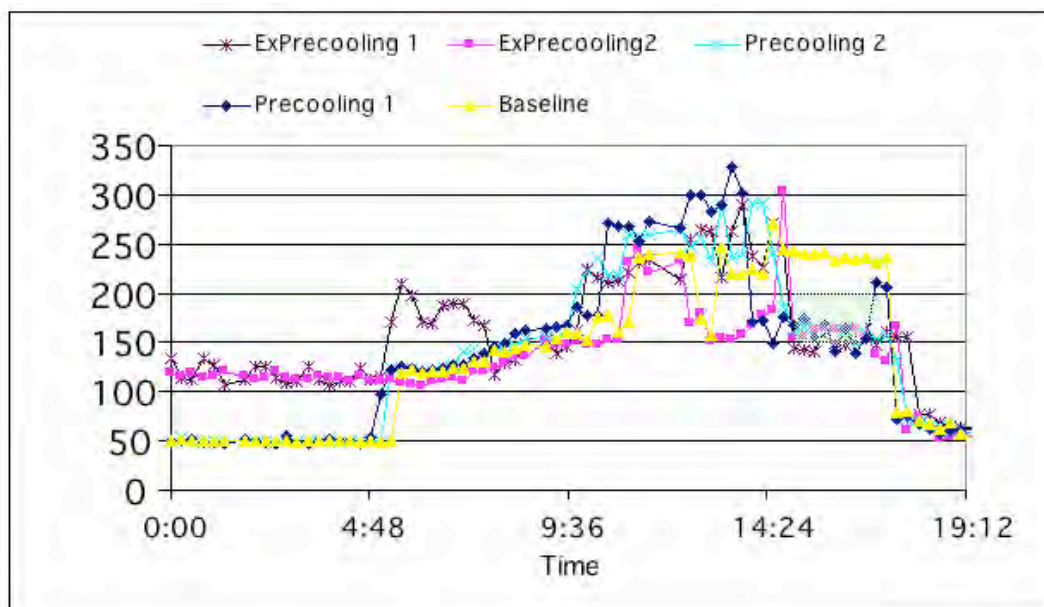


Figure 2.5 Pre-cooling tests results on cool days (Santa Rosa)

Figure 2.6 shows the effect of limited pre-cooling and extended pre-cooling on hot days. The peak outside air temperatures on these days were both 96°F and there was little difference in the solar radiation. The reduction in the whole building power was about 150 kW for two hours. In the extended pre-cooling tests, the power increased at night compared to the baseline because the system turned on to provide pre-cooling at midnight. In the morning and during the shed period, there was little difference between the electrical power consumption in the extended and limited pre-cooling tests. Part of the reason was that the HVAC system was not running close to its full capacity even on these hot days. The cooling plant is significantly oversized by as much as a factor of two. It is believed that the response would be different under the different pre-cooling scenarios if the HVAC system was close to its full capacity.

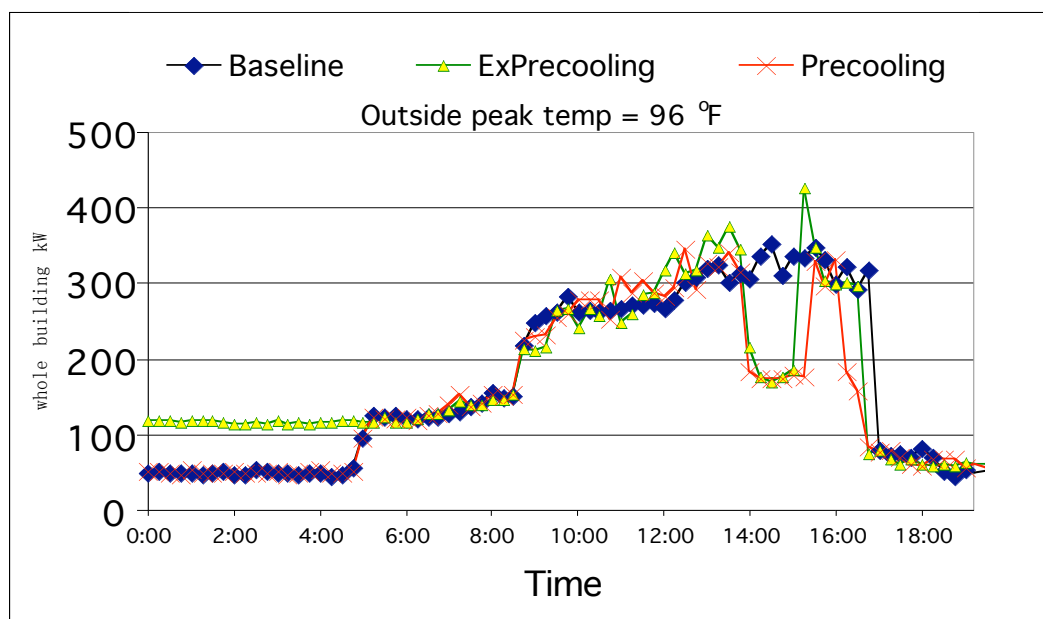


Figure 2.6 Pre-cooling test results on hot days (Santa Rosa)

Compared with the test results on hot days in 2003, the reduction in demand did not last into the unoccupied hours. There were “rebounds” at around 4 pm for both pre-cooling tests. There were two factors contributing to the difference. First, the test days in 2004 were hotter than the corresponding test days in 2003. The maximum outside air temperature in 2004 was 96°F, compared with 88°F in 2003. This increase in outside temperature increased the cooling load during the peak hours significantly, especially the ventilation load. Second, the afternoon new temperature set point was 76°F instead of 78°F, so the inside temperature would have reached the set-point more quickly even if the load had not been greater.

2.3.6 Comfort Analysis

Figures 2.7 and 2.8 show the comfort survey data collected from the Santa Rosa Federal building over the test period (See Appendix V). In these figures, the percentages of occupant responses in the different categories are used to indicate the comfort level in the building. Note that on the days when the e-mail requests were

sent, there were roughly twenty to thirty responses both in the morning and afternoon, accounting for 20 to 30% of the building occupants. This relatively large sample size gives us good confidence in the comfort estimate. There were also days when the request was not sent out but still some responses were received from the occupants. These are the days for which N is small; these data should be ignored.

As is shown in Figure 2.7, the percentage of people who felt too cool was no higher during the pre-cooling period than during the baseline period. The percentage of people who felt the room was too cool decreased slightly even though the set-point was lowered from 72°F to 70°F in the morning, suggesting that the differences in the data are statistically significant.

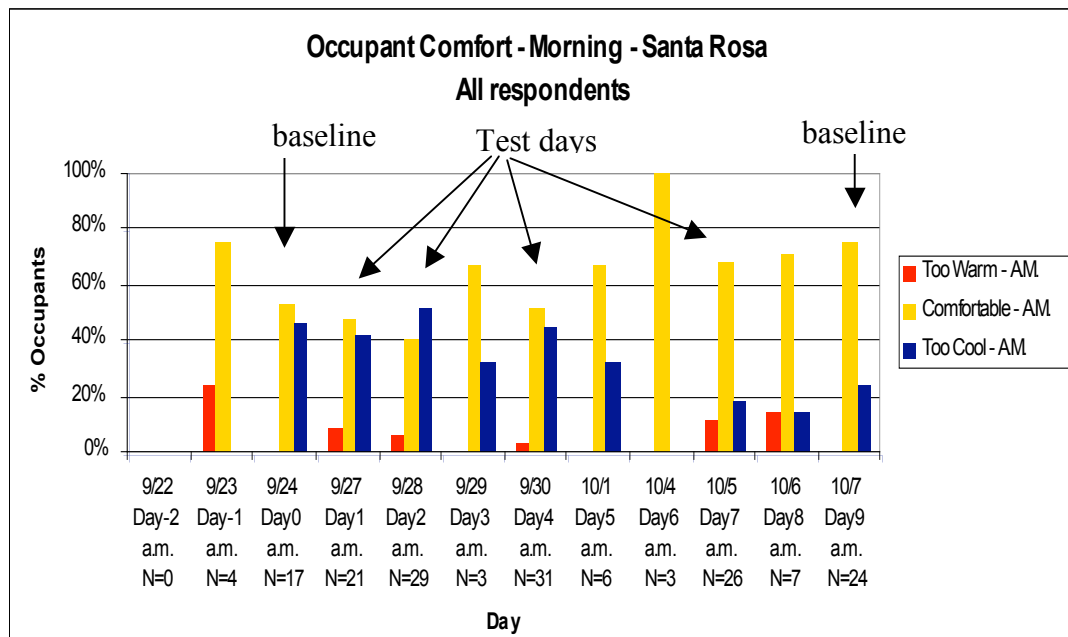


Figure 2.7 The thermal comfort response in the morning (Santa Rosa)

In the afternoon, when the temperatures were higher than for the baseline cases, the occupants did not indicate that the conditions were too warm. This is shown in Figure 2.8. The percentage of people who felt too warm did not increase from the morning to the afternoon. One limitation of these results is that all the responses were obtained on “cool” days; the phase of the study in which comfort responses were obtained ended before the period of hot weather when the “hot” day load shedding measurements were made. Given that the air temperature is not the sole determinant of comfort in a space, it is possible that higher levels of discomfort might have been experienced on “hot” day afternoons.

Figure 2.9 shows another way to illustrate the comfort level in the building before and during the test. The average values of the thermal comfort are plotted with their standard deviations. For thermal comfort, a score between -1 and +1 represents a good thermal comfort environment. In the morning, the thermal comfort in both pre-cooling and extended pre-cooling did not change from the baseline. The same thing happened in the afternoon. The variations of the average values of the thermal comfort were all within the error bars and there were no clear trends as to whether people felt colder or warmer either in the morning or in the afternoon. For

productivity, a similar conclusion can be drawn. The variation of the productivity seemed to be random with no clear trends.

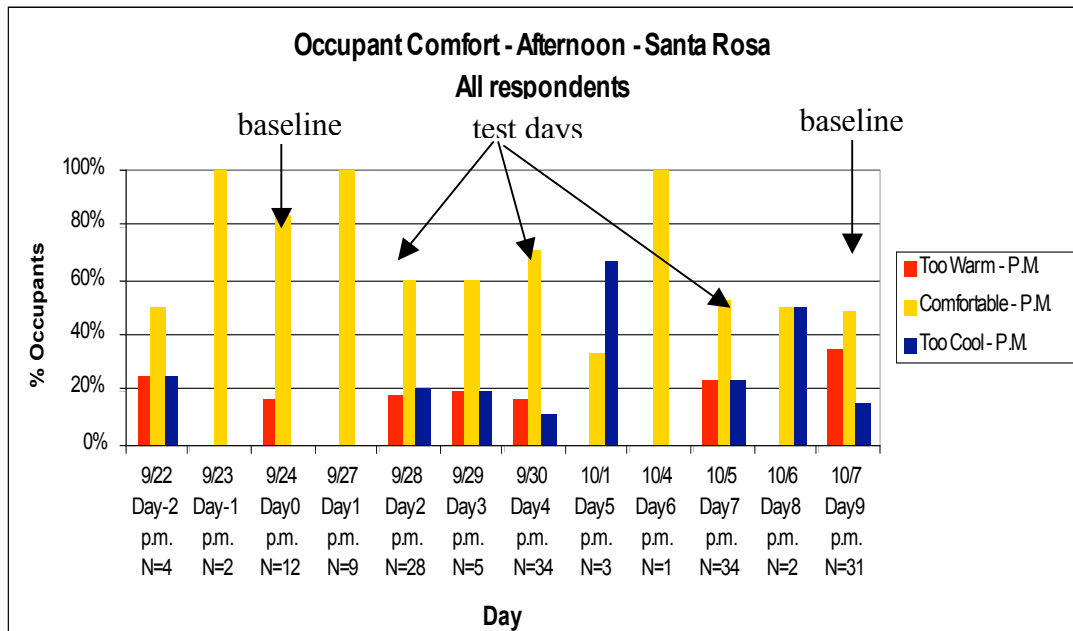


Figure 2.8 The thermal comfort response in the afternoon (Santa Rosa)

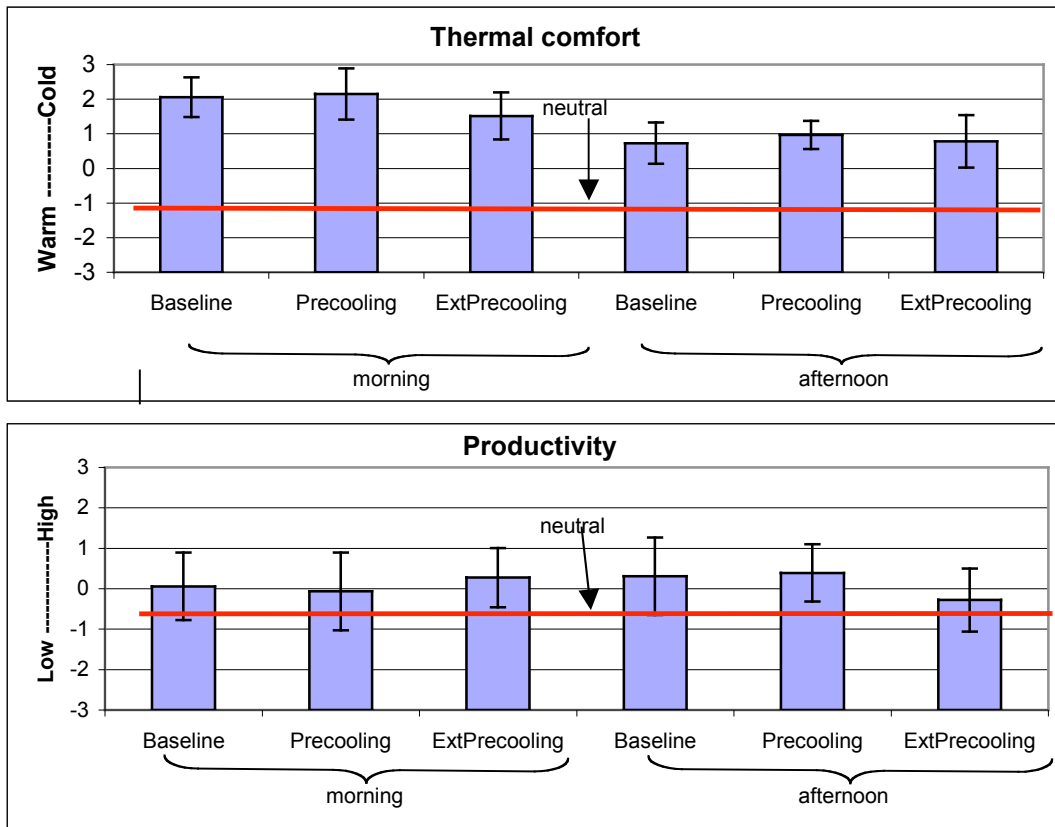


Figure 2.9 Comfort and productivity level before and during the pre-cooling tests (Santa Rosa Federal Building)

2.4 Test site 2 - McCuen Center One

2.4.1 Test Site Description

The second test site, McCuen Center One, is an 84,000 ft² office building in Rancho Cordova, California (Figure 2.10). The Class A office building, developed by McCuen Properties, is leased by the County of Sacramento's Water Quality Division and Department of General Services. The building was built in 2001 and then sold to a Bay Area investor. McCuen Properties now serves as property manager for the building. It has two stories with moderate structural mass, having 4" concrete floors and 8" exterior concrete walls. The office area has a medium furniture density and standard commercial carpet on the floor. The building has a window-to-wall ratio of 0.5. The windows are single-pane glazing with green tint. The internal equipment and lighting load are typical for office buildings. The number of occupants in the office areas is approximately 125 on the first floor and 185 on the second floor. The maximum allowable temperature in summer is 78°F because of the contract agreement between McCuen Properties and the County of Sacramento.

The building has two rooftop packaged units, each serving half of the building. The supply and return fans in the units are controlled by variable frequency drives (VFD). The air distribution system is single duct VAV. There are about 40 zones in the building. The building is fully equipped with digital direct control (DDC), but with no global zone temperature reset strategies programmed before this study.



Figure 2.10 McCuen Center One, Rancho Cordova, California

Operationally, the building is typical of many office buildings. The HVAC system starts at 6 am and pre-heats or pre-cools the building until 8 am. The occupied hours are from 8 am to 5 pm. No major faults in the mechanical system were apparent and there are relatively few comfort complaints, averaging about one to two hot or cold calls per month. The building operation is subcontracted to a local contractor who controls the building remotely. There is no in-house building operator.

2.4.2 Test Strategies

The pre-cooling and zone temperature reset strategies that were tested are shown in Figure 2.11. Extended pre-cooling was not tested in this building because of problems that were encountered in the building. The building was normally operated at a constant set point of 74°F throughout the startup and occupied hours. After 6 pm, the system was shut off and zone temperatures floated. Under normal operation, the set-points in individual zones ranged from 70 to 75°F, with an average value of 74°F. All of the zone temperature set points were lowered to 72°F From 6 am to 12 pm on the pre-cooling test days. Since the electrical summer super peak charge starts at 12 pm, the set points were raised to 76°F from 12 pm to 5 pm. After 5 pm, the system was shut off, as is done in the regular operational mode.

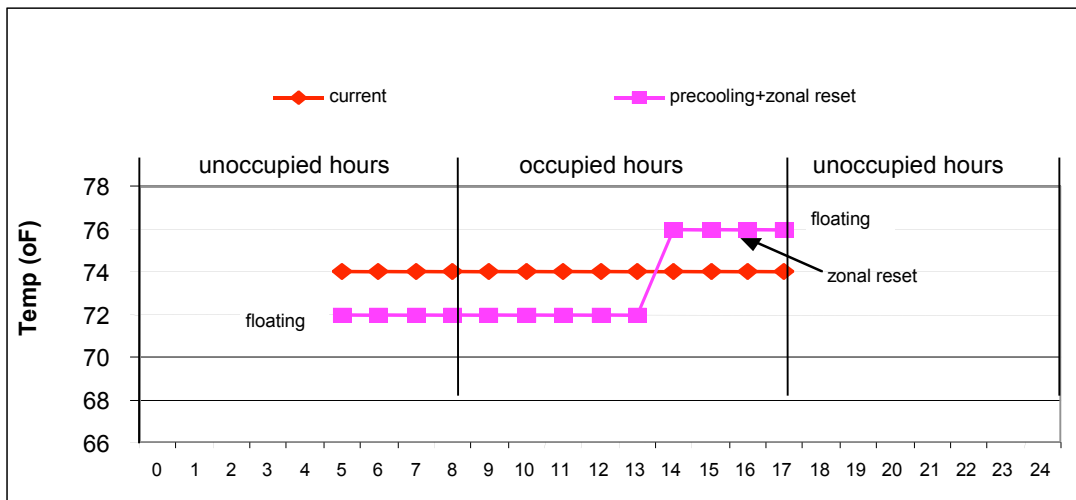


Figure 2.11 Pre-cooling test strategy for McCuen Center One

2.4.3 Monitoring Plan

There is no whole building power interval meter or sub-metering in the building. There is a weather station measuring outside air temperature and humidity. Two temporary power meters were installed on the two rooftop units for this study to determine the impact of the control strategies on HVAC power. As in the Santa Rosa Federal Building, eight operative temperature sensors were installed in the building. The operative temperature sensors consist of temperature sensors enclosed in hollow spheres that measure a weighted average of the radiant temperature and dry bulb air temperature. Because of the radiant effect, the operative temperature is a better indicator of the thermal comfort than the dry bulb air temperature. This was thought to be important in assessing thermal comfort in this study, because the building surfaces should be cooler as a result of the pre-cooling.

Trending of HVAC performance data, such as supply air temperature and duct static pressure, was set up using the building control system before the pre-cooling tests. However, these data were lost accidentally by the remote operator. The only data

available for this building was the data logger data from the power meters and temperature sensors, and weather data from the local weather station.

2.4.4 Weather and Test Scenarios

All the tests were conducted during late September 2004, when the weather had started to cool down in the region. Due to the early fall conditions, tests were conducted on relatively cool days, when the peak outside air temperature was between 72°F and 75°F. In total, three morning pre-cooling and zonal temperature set up tests were conducted at this building. Each test lasted for one day.

2.4.5 Results

Figure 2.12 shows the pre-cooling tests results for McCuen Center One. The shaded area is the amount of the electrical peak load shifted. In all three tests, the morning electrical load is almost same as the baseline. At 12 pm, when the zone set-point was raised to 76°F, the HVAC system almost completely shuts down in all three tests. The maximum shed was about 40 kW and the sheds lasted roughly about 2 hours. The energy savings in the peak hours were roughly about 100 kWh. The cause of the spike in the baseline is unknown. Note that the spike of the electrical peak that was seen in the baseline was avoided in all three tests.

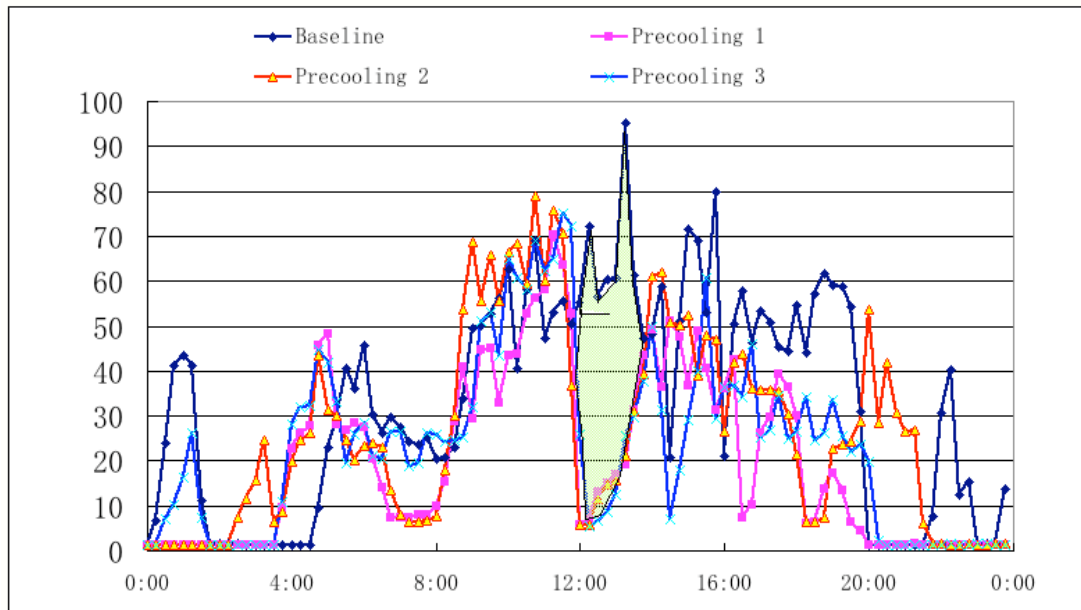


Figure 2.12 Pre-cooling test results in McCuen Center One – HVAC power

2.4.6 Comfort Analysis

Figures 2.13 and 2.14 show the comfort survey data collected from McCuen Center One over the test period. On the days when e-mail reminders were sent out, there were roughly eighty to ninety responses each time, accounting for 30-40% of the building occupants. In the morning, as is shown in Figure 2.13, the percentage of respondents who felt too cold increased from 20% to about 60% compared with baseline, which indicated that the room was perceived to be significantly cooler than

the baseline. However, in the afternoon, as is shown in the Figure 2.14, when the temperatures were higher than the baseline, the respondents did not perceive the room as warmer. The afternoon data are consistent with what was observed in the Santa Rosa Federal Building. The percentage of respondents who felt warm did not increase significantly when the temperature increased by 2 degrees.

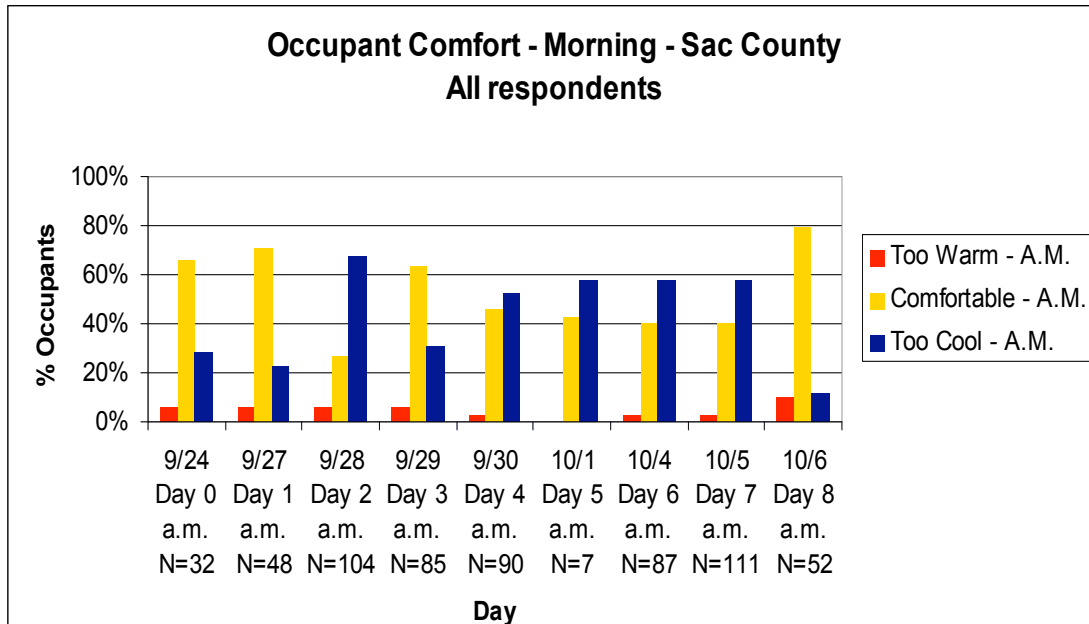


Figure 2.13 The thermal comfort response in the morning (McCuen Center One)

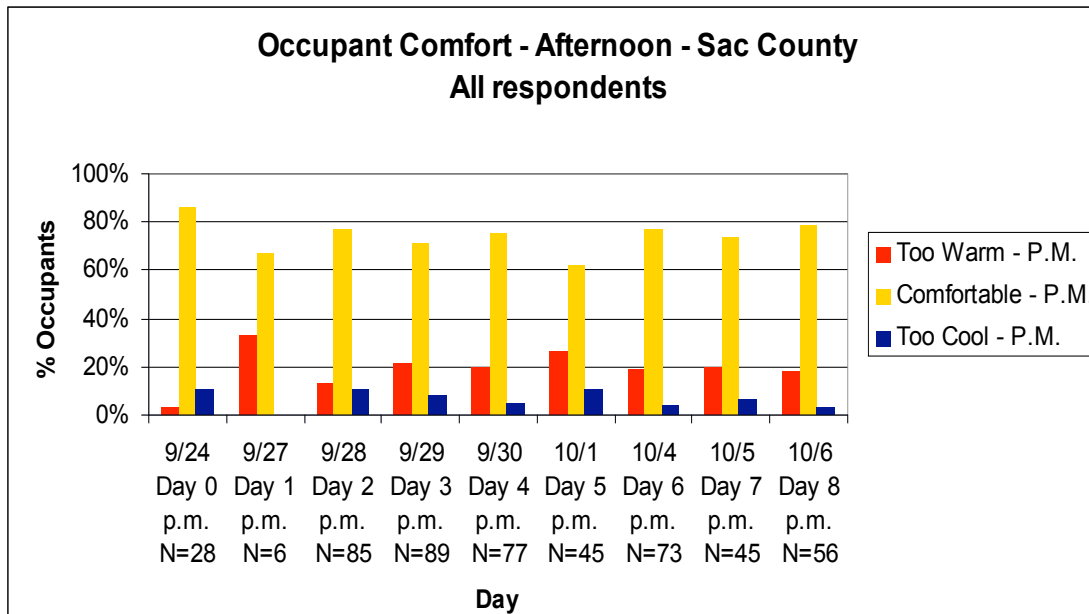


Figure 2.14 The thermal comfort response in the afternoon (McCuen Center One)

Figure 2.15 is another way to present the data in terms of the average values of the thermal comfort and productivity. The same conclusions can be drawn from the

averages as from the percentage plot. Basically, there was a decline in the thermal comfort and productivity in the morning and no changes in the afternoon.

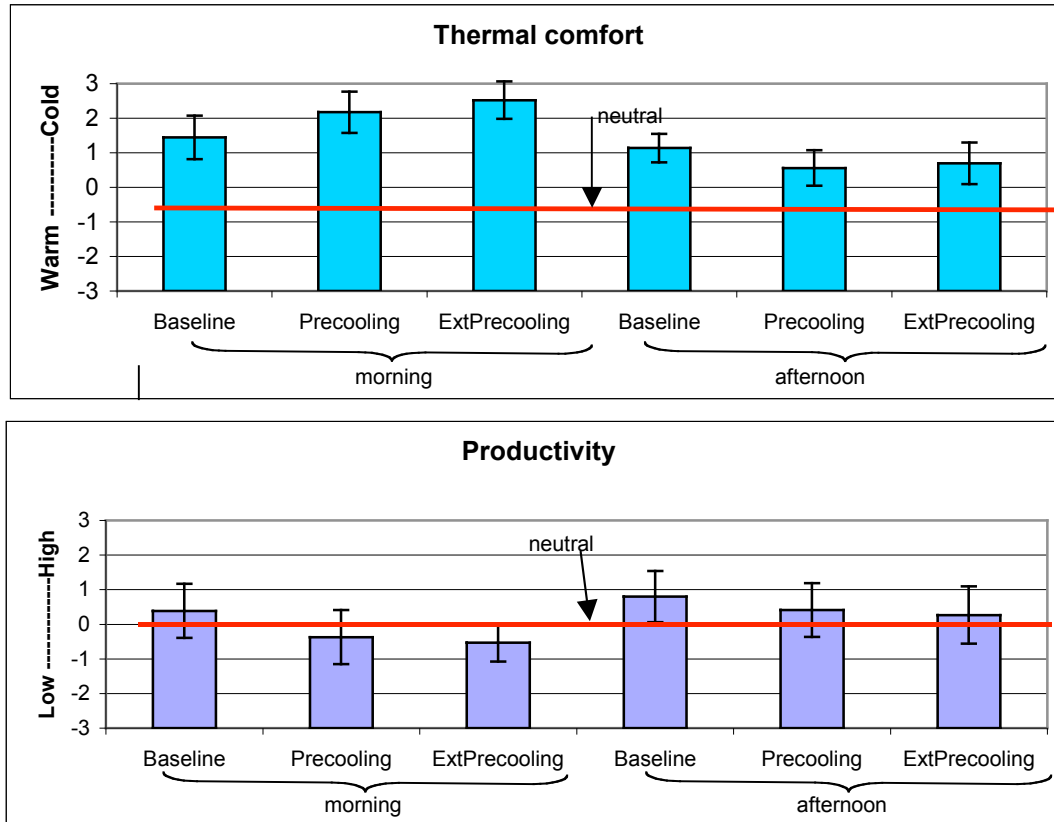


Figure 2.15 Comfort and productivity level before and during the pre-cooling tests (McCuen Center One)

So why did people start to feel significantly cooler when the morning set points were decreased by only two degrees, from 74°F to 72°F? Why did this not happen in Santa Rosa Rosa Federal building? The zone temperature data from the temperature loggers were plotted to examine what had happened in the tests. Figure 2.146 is a plot of the typical zone temperature before and during the tests. On the test days, although the zone temperature did go below 70°F occasionally, most of the time the temperature in the morning was above 72°F. Figure 2.17 is a plot of the temperature in the coldest zone. In this zone, the temperature was as low as 65°F in one particular test. So, for certain zones, it was cold in the morning, and much colder than we expected it should be, since the set point was only adjusted down to 72°F. One possible explanation is that, on cool weather days (daytime peaks of about 75°F) the early morning outside temperature was only about 60°F. This would cause perimeter zones with low internal heat gains, such as zones on the second floor of the west wing, to switch into heating mode. Since the boiler had been locked out for the pre-cooling tests, the zone temperature would fall below the cooling set-point. One conclusion to be drawn from this is that equipment schedules should not be interfered with if the basis of the demand-shifting strategy is to change zone set-points.

Another possible explanation is that there could have been significant temperature variations within the space, so that the temperature in the vicinity of the thermostat could have met the set-point while the temperature in the vicinity of the data logger whose measurements are shown in Figure 2.17 could have been significantly less. There were known to be air balance problems in that part of the building that could have had this effect.

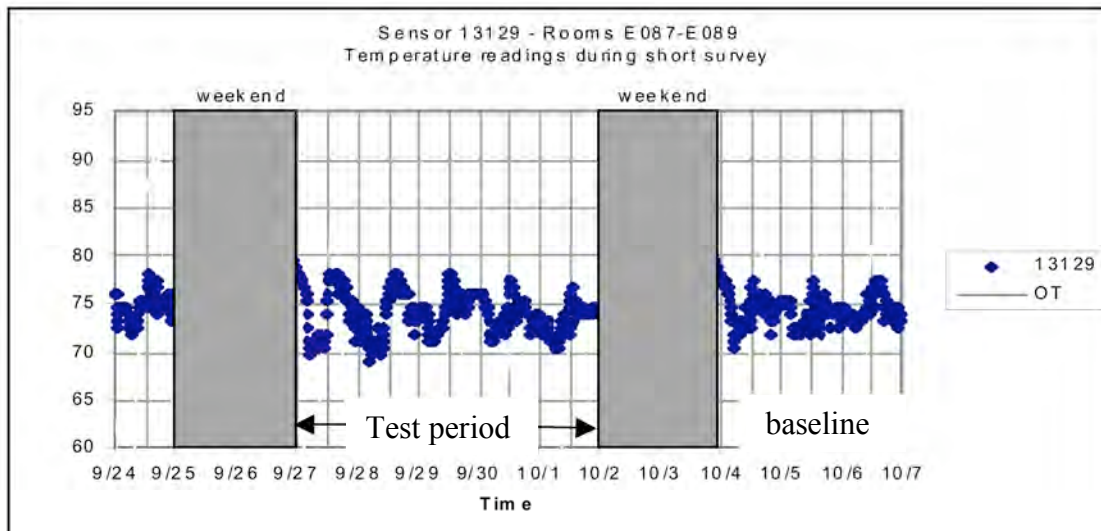


Figure 2.16 Temperatures in a typical zone before and during the pre-cooling tests. (McCuen Center One)

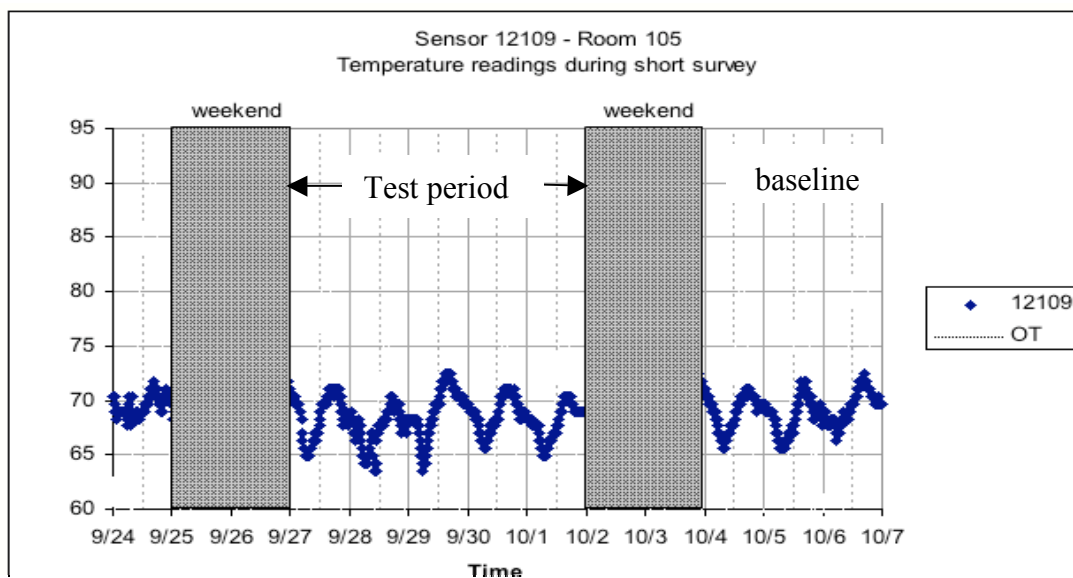


Figure 2.17 Temperature in the worst zone before and during pre-cooling tests (McCuen Center One)

3. SIMULATION AND STRATEGIES ANALYSIS

3.1 Introduction

The field test results in both buildings demonstrated that large peak demand reduction can be obtained if pre-cooling and demand limiting strategies are implemented correctly. However, since only limited tests were conducted over a short period, EnergyPlus simulations were used to help understand more about the buildings' dynamics and evaluate various strategies. There were several important issues that were not addressed in the field tests:

1. It is not clear what would happen if the temperatures were reset in the peak hours without pre-cooling. One possibility is that the load reduction will be nearly as much as with pre-cooling.
2. The effects of nocturnal pre-cooling are still unclear. Night pre-cooling appeared to produce very modest effects in the Santa Rosa Federal building. There was no opportunity to test nocturnal pre-cooling in the McCuen Center One building. In theory, the effects during the following morning should be more significant than in the afternoon. In fact, there are contradictory reports in the literature of tests of the effect of nocturnal cooling on the afternoon period (Ruud et al 1990) (Mahajan et al. 1993).
3. The importance of recovery strategies was realized at the end of the field tests when recovery was observed to be a problem on the hot days. However, there was no opportunity to test any of these strategies in the field. There are two temperature reset sequences worthy investigating, namely the linear reset, in which the temperature increases at a constant rate to the maximum temperature over the shed period, and exponential reset, in which the temperature increases faster in the beginning and slower in the end. It is important to understand the building response under these two strategies and compare the advantages and disadvantages of them.

EnergyPlus, DOE's successor to DOE-2, was used for the simulation work. Compared to DOE-2, EnergyPlus has a number of advantages. It solves for the building load and mechanical system response simultaneously, which is a significant advantage for demand response studies, where the zone temperatures are not always at their set-point. In addition, the time-step can be significantly less than one hour – fifteen minute time-steps were used in this study.

In this study, the simulation model was constructed first and then the measured data were used to calibrate the model. It is difficult to simulate building operation exactly and match the utility data hour by hour. Since the main focus of the study was to evaluate different building control strategies, the initial models were debugged and the parameters were adjusted till the hourly simulation profile matched the data collected in the field.

Six simulations were conducted for each building:

- 1) *Baseline*. The simulation is based on normal building operation.
- 2) *Zonal reset only*. There is no pre-cooling. The zone temperature set point is increased by a few degrees during the on-peak period.
- 3) *Pre-cooling and zonal reset*. Pre-cool the buildings during the morning off-peak period and set up the zone temperature by few degrees during the on-peak period.
- 4) *Extended pre-cooling and zonal reset*. Pre-cool the building starting from midnight and continue throughout the morning until the start of the on-peak period, then set up the zone temperature by few degrees during the peak period.
- 5) *Pre-cooling and linear zonal reset*. Pre-cool the building as in Strategy 3 then increase the zone temperatures linearly to the new on-peak set-point.
- 6) *Pre-cooling and exponential temperature reset*. Pre-cool the building as in Strategy 3 then increase the zone temperatures exponentially to the new on-peak set-point.

3.2 Simulation of the Santa Rosa Federal Building

3.2.1 Model Description

The EnergyPlus model is based on the mechanical system layout and zoning of the building. The west side of the building is divided into six zones, two zones per floor. There are two AHUs, each serving three zones. The air distribution system is a dual duct VAV system with a deadband of four degrees between the zone heating and cooling set-points. The return air flows through ducts located in plenums above the occupied spaces.

The geometry of the model is shown in Figure 3.1. The geometry information was collected from the scanned architecture drawings in AutoCAD. The lighting power density and equipment load were estimated during inspections of the building.

To simplify the cooling plant, instead of simulating three chillers, one large variable speed chiller was used in the model. The one chiller should give a reasonable approximation to the performance of three small chillers with multiple stages. The simulated cooling plant was oversized to the same extent as in the real building.



Figure 3.1 The EnergyPlus model geometry for the west side of the building (Santa Rosa)

3.2.2 Simulation Scenarios

Figures 3.2 and 3.3 show the temperature set-point profiles and operating hours for the simulations performed to determine the effect of the nocturnal pre-cooling and morning pre-cooling, respectively. By comparing the electrical demand of zonal reset with and without pre-cooling, the impact of pre-cooling can be determined. By comparing the electrical demand of pre-cooling with zonal reset to extended pre-cooling with zonal reset, the effects of night pre-cooling can be determined.

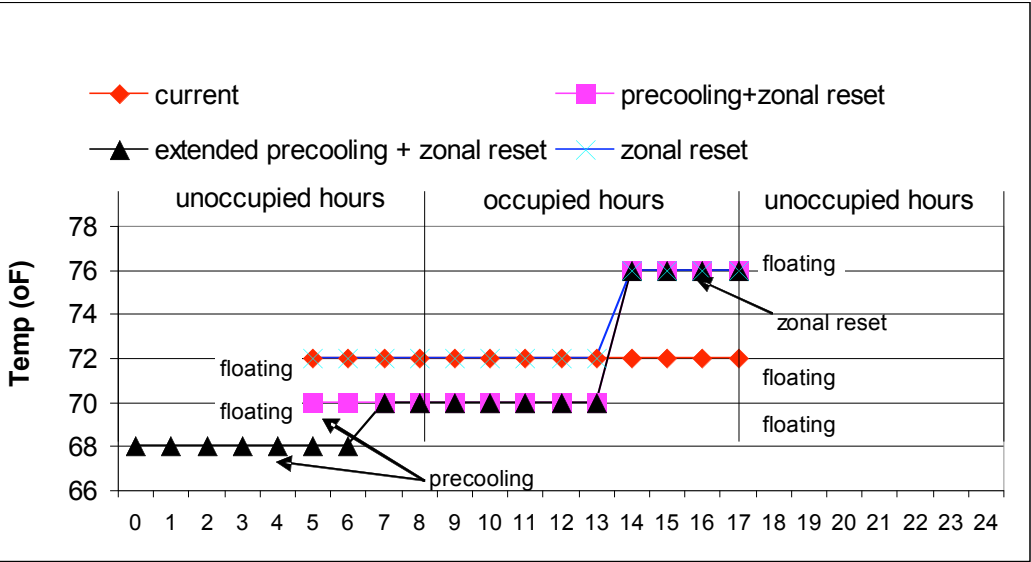


Figure 3.2 Pre-cooling and zonal reset strategies used in the simulation (Santa Rosa)

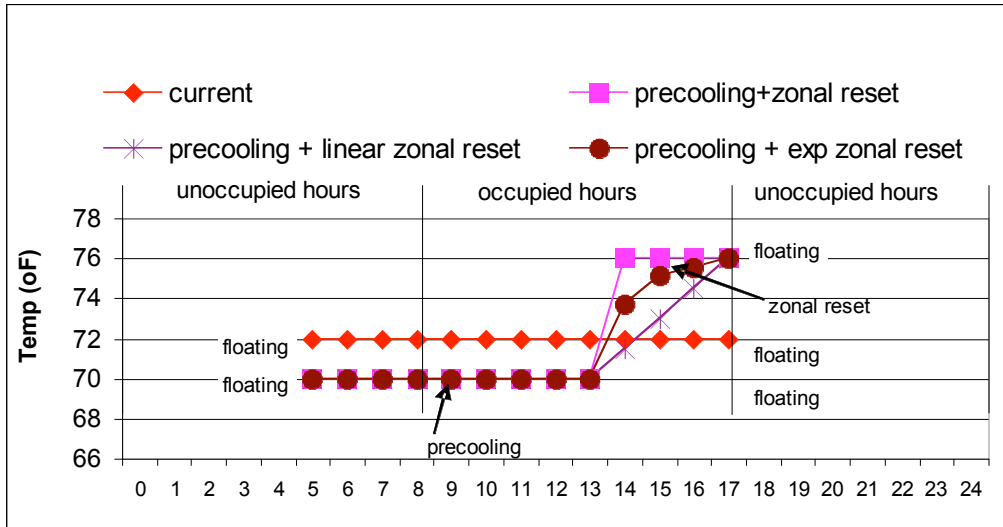


Figure 3.3 Demand limiting and recovery strategies used in the simulation (Santa Rosa)

3.2.3 Simulation Results

Figure 3.4 shows the simulated chiller power for a hot summer day for various pre-cooling strategies. The outside air temperature profile for the simulated hot summer day is similar to those of the hot test days.

Zonal reset only. Zonal reset without pre-cooling produces an immediate load shed of almost the same magnitude as that produced after pre-cooling. However, the shed does not last as long as after pre-cooling. The chiller power increases more quickly and rises to a higher level.

Pre-cooling with zonal reset. Compared with the baseline, the chiller power is a bit higher in the morning before the peak period. However, during the peak period, the chiller power is significantly less than that observed without pre-cooling. The cooling load, and hence the electrical demand, is moved from the on-peak period in the afternoon to the off-peak period in the morning.

Extended pre-cooling with zonal reset. The shed during the on-peak period is almost identical to the shed obtaining using the morning-only pre-cooling strategy. The extended pre-cooling shifts the morning load a bit, but not as much as expected. Note that there is no chiller power consumption during the night because the outside air temperature is low enough that chiller operation is not needed in order to meet the supply air temperature set-point. During the on-peak period, the extended pre-cooling decreases the load by a very small amount compared to morning-only pre-cooling. This agrees with our experiment data collected from the site. The effects of extended pre-cooling in this building are very limited.

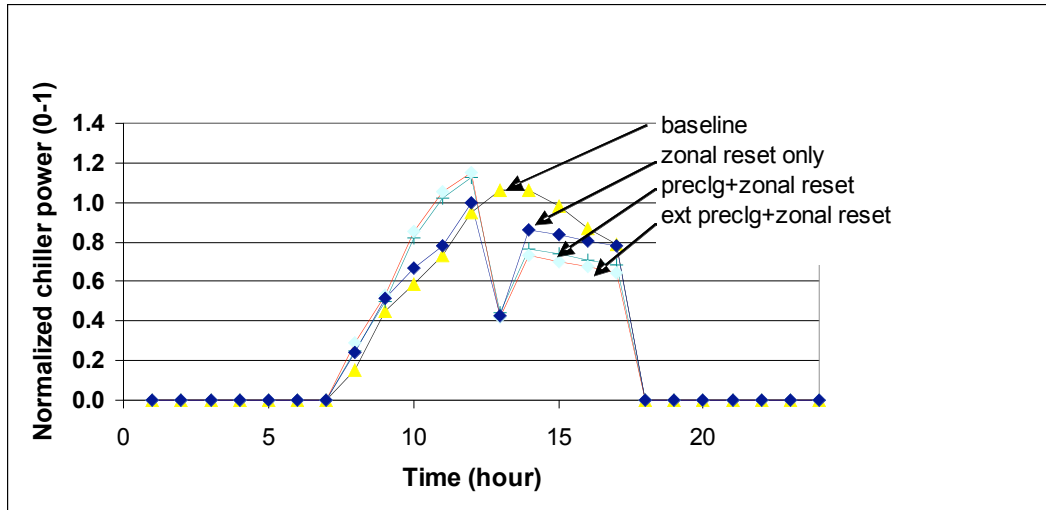


Figure 3.4 Simulated chiller power under various pre-cooling strategies (Santa Rosa)

Figure 3.5 shows the simulation results of various set-point trajectories during the on-peak period. Notice that in the simulation results shown in Figure 3.4, the chiller comes back on in the afternoon and creates a second peak. The more ideal scenario is to charge the thermal mass more smoothly and to create a flat power profile in the afternoon. Figure 3.5 shows the chiller power over a 24 hour period for various demand discharge strategies. Notice that the integrated load shed is almost same for all the strategies, which is to be expected since the heat capacity is unchanged.

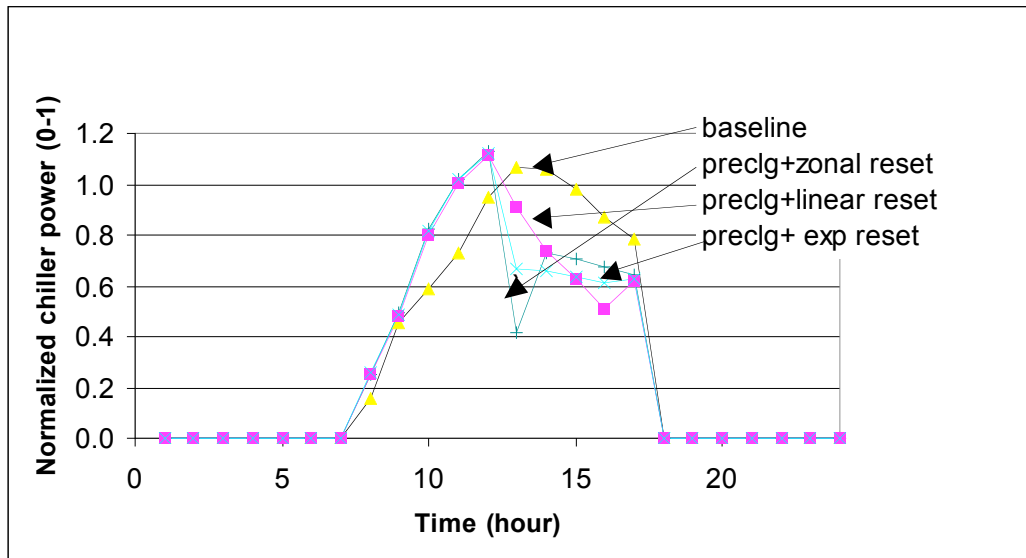


Figure 3.5 Simulated chiller power under various zonal reset strategies (Santa Rosa)

Pre-cooling and linear zonal reset. Compared to the morning pre-cooling with zonal reset, the chiller power varies more smoothly. The shed is not as drastic as the instant reset but there is still a little rebound just before the end. However, the electrical power profile is much improved.

Pre-cooling and exponential zonal reset. This strategy achieves the best power profile of all the scenarios. The power is essentially constant during the on-peak period and there is no “rebound”.

3.3 Simulation of McCuen Center One

3.3.1 Model Description

The EnergyPlus model built for the McCuen Center One building is also a simplified model. The building has two floors and two rooftop package units. The building was divided into ten zones, five zones on each floor. On each floor, there is an interior zone and four exterior zones facing north, south, east, and west. The lighting power density and equipment load were estimated during inspections of the building. The air distribution system is single duct VAV. The geometry of the simulation model is shown in Figure 3.6

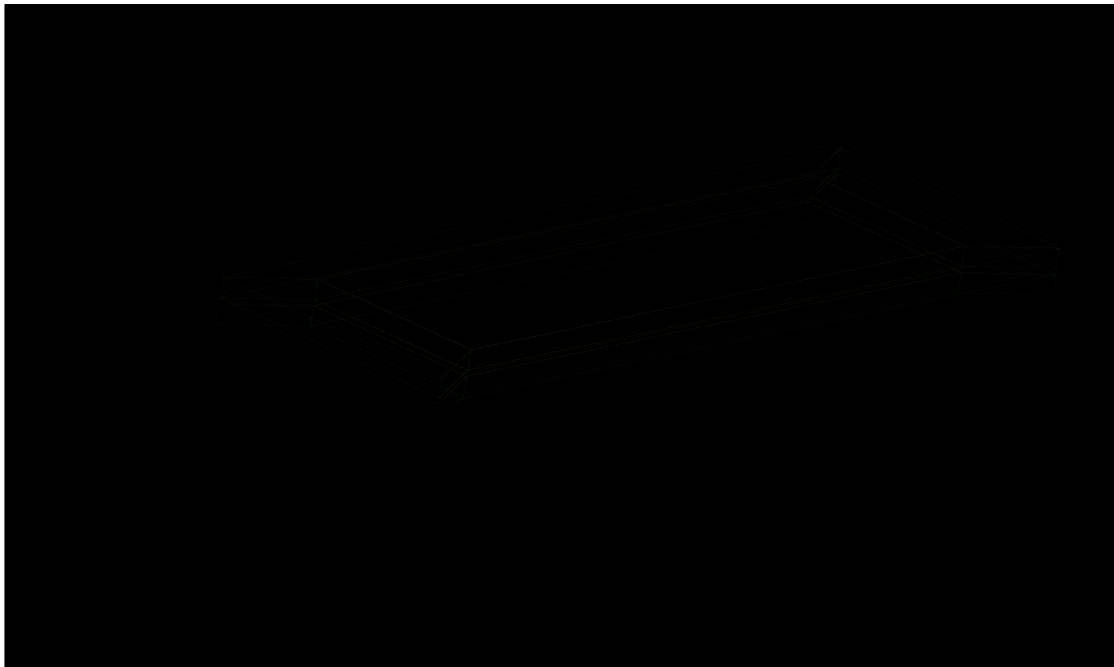


Figure 3.6 Building geometry of the EnergyPlus model (McCuen Center One)

3.3.2 Simulation Scenarios

The simulation scenarios are identical to those for the Santa Rosa Federal building. Six cases were simulated to identify the effects of the morning pre-cooling, night pre-cooling and various recovery strategies. Figure 3.7 and 3.8 shows the temperature set-point profiles and operating hours for the simulations performed to determine the effect of the nocturnal pre-cooling and morning pre-cooling.

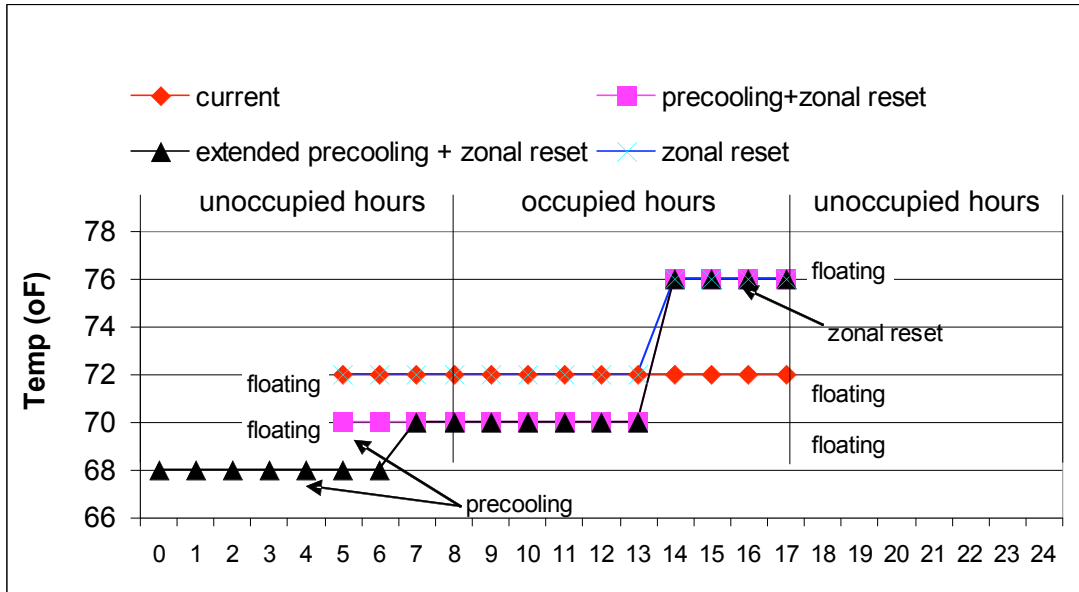


Figure 3.7 Pre-cooling and zonal reset strategies used in the simulation (McCuen Center One)

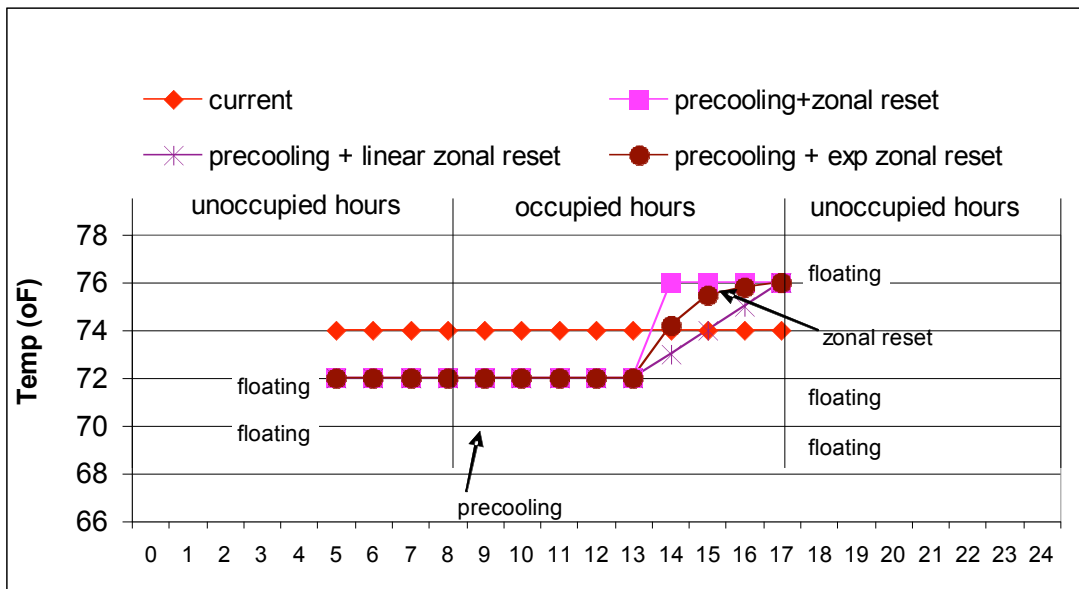


Figure 3.8 Demand limiting and recovery strategies used in the simulation (McCuen Center One)

3.3.3 Simulation Results

Figure 3.9 to 3.12 show the simulation results for McCuen Center One. The outside air temperature profile for the simulated hot summer day is similar to those of the hot test days. Since rooftop units are used in this building, it is essential to separate the fan power usage and compressor power usage. Two plots were made under each scenario. One is the total electricity power and the other is the cooling load.

Figure 3.9 and 3.10 shows the rooftop unit total electricity and cooling load under various pre-cooling strategies. The total electricity power agrees well with the field results for the morning pre-cooling with zonal reset test.

Zonal temperature reset only. Compared with pre-cooling strategies, the shed is not as deep and does not last as long as the pre-cooling strategies. Zonal reset without pre-cooling produces an immediate load shed of smaller magnitude than that produced after pre-cooling. The shed does not last as long as after pre-cooling and the chiller power rises to a higher level.

Morning pre-cooling with zonal reset. In the morning period, both the total power and the cooling load are slightly higher than the baseline. When the set-point is increased at 12 pm, the total power and the load are each immediately reduced by about 50%. However, the shed does not last very long; the temperature increase quickly and the total power and the load reach new peaks at about 4 pm.

Extended pre-cooling with zonal reset. In the morning period, the electrical load is only slightly lower than with morning-only pre-cooling. In the on-peak period, the magnitude of the shed is significantly greater than with morning-only pre-cooling and the rebound is significantly reduced.

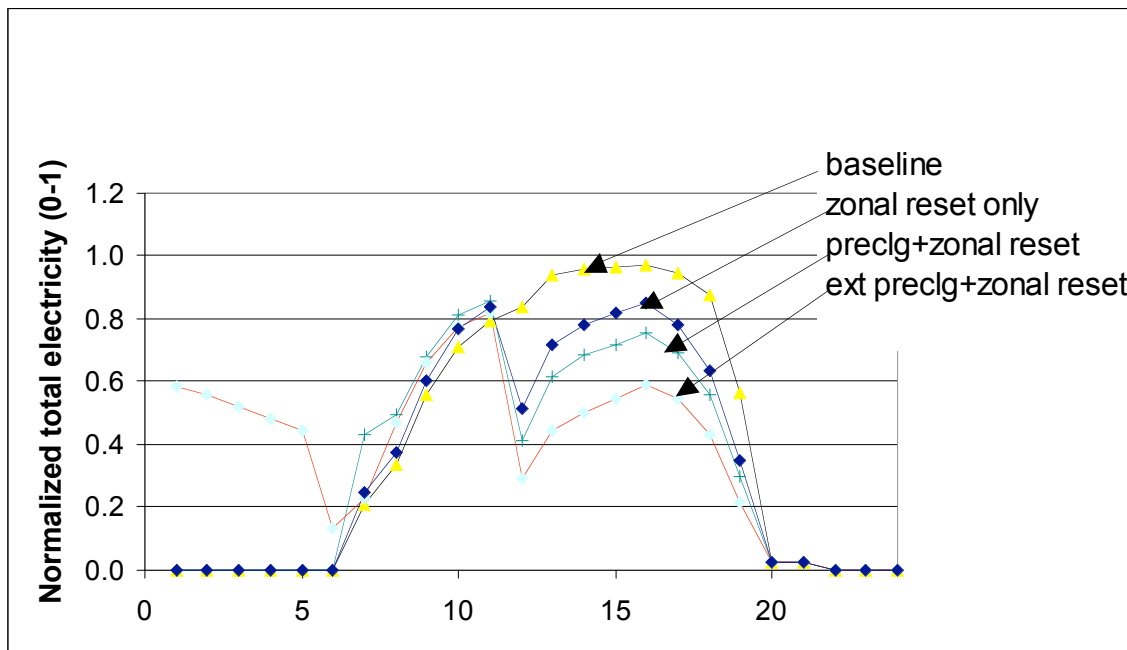


Figure 3.9 Rooftop unit total electricity under various pre-cooling strategies (McCuen Center One)

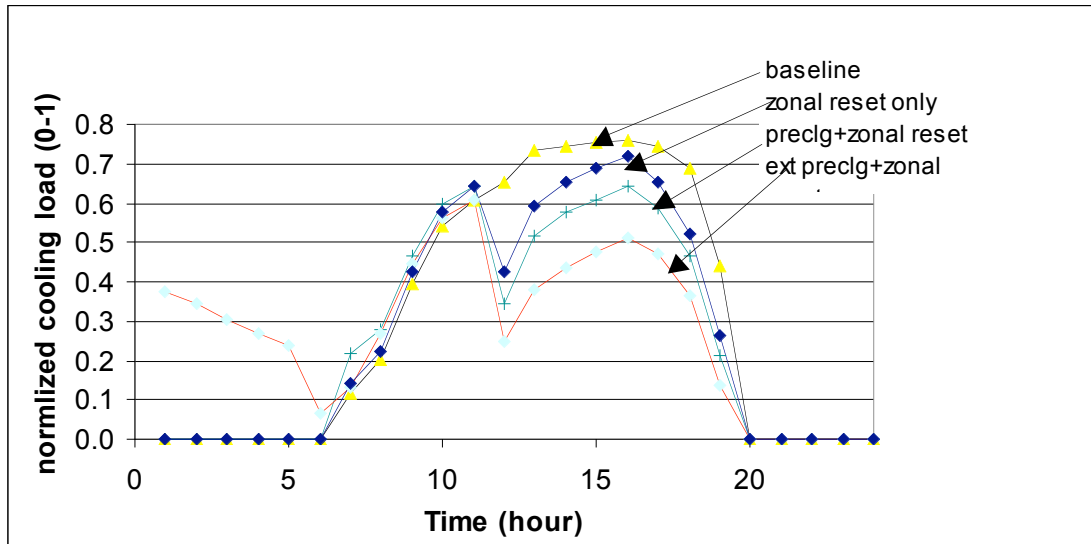


Figure 3.10 Rooftop unit cooling load under various pre-cooling strategies (McCuen Center One)

The main result is that extended pre-cooling produces significantly deeper shedding, at the expense of substantial energy use during the night, resulting in a significant energy penalty. This result for McCuen Center One contrasts with the results for the Santa Rosa Federal Building, where both the simulation results and the field tests showed little or no benefit from extending the pre-cooling period. This result should be investigated further to determine the critical factor producing the difference in response and verify that the result is not spurious.

Figure 3.11 and 3.12 show comparisons of various temperature-reset strategies. As was found for the Santa Rosa Federal building, the load profile for the exponential profile is the best, producing an essentially constant load and the lowest peak demand.

Figure 3.11 Rooftop unit total electricity consumption for different temperature-reset strategies (McCuen Center One)

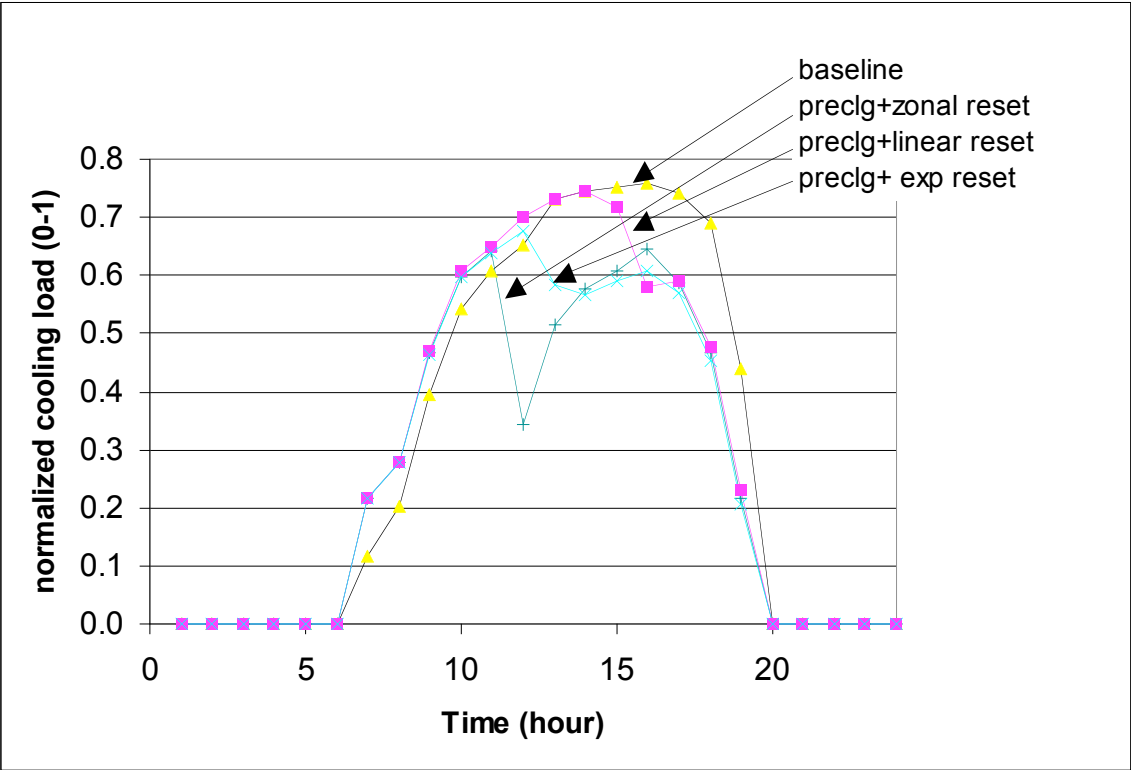


Figure 3.12 Rooftop unit cooling load under various pre-cooling strategies (McCuen Center One)

4. CONCLUSIONS AND DISCUSSION

4.1 Field Tests

The following conclusions can be drawn from the field tests of pre-cooling strategies in the two commercial buildings:

1. The comfort surveys indicate that comfort can be maintained in both pre-cooling and afternoon reset if the zone temperatures are kept within the specified ranges. In the Santa Rosa Federal building, the comfort and self-assessed productivity levels did not vary significantly during the pre-cooling tests, while the zone temperatures varied between 70 and 76°F during the occupied period. In the Sacramento building, the comfort and productivity in the afternoon were maintained when the set-point was raised from 72°F to 72°F. In the morning, the comfort level was decreased only because the zone temperature was much lower than the desired set point of 70°F. Therefore, it is inferred that a properly implemented pre-cooling strategy should not cause comfort problems in buildings.
2. It was found that nocturnal pre-cooling has varying effects on the magnitude of the peak the following day, with a number of factors affecting its effectiveness. The 2004 results from the Santa Rosa Federal building are similar to those obtained in 2003. The nocturnal pre-cooling has a marginal effect during the following morning, but has no discernible effect during the on-peak period in Santa Rosa Federal building. Extended pre-cooling was not tested in the McCuen Center One building. The results of an investigation using simulation are summarized below.
3. The strategy for managing the demand during the on-peak period is important, particularly on hot days or in buildings with smaller time constants, where electrical power can rebound after a short period. This was not a problem in the tests in the Santa Rosa Federal building in 2003 because the on-peak set-point was higher (78°F vs 76°F) and there were no tests on very hot days, so the set-point was not reached during the occupied period and the chillers remained off. These conditions did not apply in the 2004 tests and, as a result, avoiding significant load variations during the afternoon became an issue. An exponential zone temperature set-point trajectory was found to produce negligible variation in load during the on-peak period and therefore is recommended for practical implementation.
4. It is important to address any comfort problems in the building that could be exacerbated by changes in set-point before running any demand-shifting control strategies. In some cases, the problem may be a zone temperature sensor that has drifted, causing an offset in the actual temperature relative to the desired temperature. As the set-point moves away from the center of the comfort range, this offset can have an increasingly greater effect on comfort. If the problem is more complicated, some degree of retro-commissioning may be required. For example, if air balance problems cause significant variations in temperature within a zone controlled by a single temperature sensor, recalibrating the sensor will not help when the strategy is to change the set-point over the whole of the acceptable

comfort range. If the whole zone is receiving less airflow than necessary and has proportional-only control (as opposed to proportional plus integral (PI) control), the zone will suffer in two ways: it will be less effectively pre-cooled and it will be less able to maintain set-point during occupancy, both during normal periods or during periods when the set-point is increased.

4.2 Simulation

The simulation results for both buildings confirmed the results of the field tests that increasing the zone temperature set-point by four degrees can reduce chiller electricity consumption by about 33% and HVAC electricity consumption by about 25% over a four hour shed, even on hot days. The results also indicate the value of pre-cooling in maximizing the electrical shed in the on-peak period. By lowering the zone temperature by two degrees in the morning off-peak period, the on-peak shed resulting from raising the set-point by four degrees is increased by about 50%. Whether or not pre-cooling is used, the dynamics of the shed need to be managed in order to avoid charging the thermal capacity of the building too quickly, resulting in high cooling load and electric demand before the end of the shed period. An exponential trajectory for the zone set-point during the shed yielded good results and is recommended for practical implementation.

The simulation results also indicate that the effect of the extended pre-cooling can vary significantly. The result for the Santa Rosa Federal Building was that there is almost no effect, which is what was observed in the field tests. For McCuen Center One, nocturnal pre-cooling increased the shed by about 30%, though with a significant off-peak energy consumption penalty. Further work is required to determine the key building and HVAC system characteristics that determine the effect of nocturnal pre-cooling on on-peak electricity consumption.

4.3 Future Work

This study has identified several uncertainties that should be resolved before pre-cooling can be reliably implemented in large commercial. The following work is proposed:

- **Conduct field tests over a wider range of conditions.** Because of funding delays in both 2003 and 2004, most of the tests were conducted at the end of the summer and only a few tests were actually conducted on hot summer days. In 2004, no comfort data was collected on hot days. All the tests in 2003 and 2004 were blind tests where the occupants were not informed in advance that the temperature would vary. If the occupants are informed of the pre-cooling tests in advance and know to expect a temperature change, they might wear different clothes, dress in layers, and adjust their clothing level in response to temperature changes – thus extending their personal comfort zone and enabling larger power sheds.
- **Develop and test a method to determine building thermal mass metrics.** There are two key parameters affecting pre-cooling performance: the effective building thermal mass and the thermal conductance between the thermal mass and the zone air. The first parameter determines how much heat can be stored in the mass for a given temperature change, while the second one determines the heat

transfer rate for charging and discharging the thermal mass. One metric of interest is the building time constant, calculated by dividing the thermal capacity by the thermal conductance, which determines the timescale of the response to increases in zone temperature set-point.

- **Develop strategies for managing the demand during the on-peak period and test them in the field.** These strategies can be studied and developed using simulations. They can then be tested in real buildings.
- **Develop a screening tool based on simplified simulation to quickly assess DR potentials for a specific building.** What is needed is a simple screening tool that can be used for quick assessment by analyzing the impact of the climate, the building envelope, the schedule and the utility tariffs. The conventional way in which detailed simulation programs such as EnergyPlus are used is too expensive for this application because too much input data is required. One approach is to develop an inherently simple tool. The other approach is to develop a context-sensitive defaulting procedure for a more detailed tool such as EnergyPlus. These two approaches should be investigated before choosing which one to adopt.
- **Develop guidelines for appropriate control strategies according to building characteristics.** Different buildings with different mechanical systems and different levels of control may require different pre-cooling strategies. For example, the zone temperature set-point strategies studied in the work reported here are only practicable if the zone temperatures are controlled by networked digital controllers. A detailed guide to selecting, implementing and testing demand-shifting control strategies is needed to support their routine use.

References:

- ASHRAE. 2005. Handbook of Fundamentals. American Society of Heating, Refrigeration and Air Conditioning Engineers. Atlanta, GA.
- Andresen, I. and M.J. Brandemuehl. 1992. Heat Storage in Building Thermal Mass: A Parametric Study. *ASHRAE Transactions* 98(1).
- Balaras C. A. 1996. The Role of Thermal Mass on the Cooling Load of Buildings. An overview of computational methods. *Energy and Buildings* 24 (1996):1-10.
- Becker R., Paciuk M. 2002. Inter-related Effects of Cooling Strategies and Building Features on Energy Performance of Office Buildings. *Energy and Buildings* 34(2002): 25-31.
- Braun, J.E. 1990. Reducing Energy Costs and Peak Electrical Demand Through Optimal Control of Building Thermal Storage. *ASHRAE Transactions* 96(2):876-888.
- Braun, J.E. 2003. Load Control Using Building Thermal Mass. *ASHRAE Transactions* 125(1):292-301.
- Chaturvedi, N. 2000. Analytical Tools for Dynamic Building Control. *Report No. HL2000-15*, Herrick Laboratories, Purdue University, West Lafayette, Indiana.
- Chaturvedi, N. and J.E. Braun. 2002 An Inverse Gray-Box Model for Transient Building Load Prediction. *International Journal of Heating, Ventilating, Air-Conditioning and Refrigerating Research* 8(1)
- Coniff, J.P. 1991. Strategies for Reducing Peak Air Conditioning Loads by Using Heat Storage in the Building Structure. *ASHRAE Transactions* 97:704-709.
- Keeney, K.R. and J.E. Braun. 1997. Application of Building Pre-cooling to Reduce Peak Cooling Requirements. *ASHRAE Transactions* 103(1):463-469.
- Mahajan Sukhbir, Newcomb Charles, Bluck Steven, Ehteshamzadeh Robert. 1993. Optimizing the Use of Energy Management and Control Systems to Reduce Peak Load and Energy Consumption in Non-residential Buildings. *Report to California Institute for Energy Efficiency and Sacramento Municipal Utilities District*.
- Morris, F.B., J.E. Braun, and S.J. Treado. 1994. Experimental and Simulated Performance of Optimal Control of Building Thermal Storage. *ASHRAE Transactions* 100(1):402-414.
- Rabl, A. and L.K. Norford. 1991. Peak Load Reduction by Preconditioning Buildings at Night. *International Journal of Energy Research* 15:781-798.
- Ruud, M.D., J.W. Mitchell, and S.A. Klein. 1990. Use of Building Thermal Mass to Offset Cooling Loads. *ASHRAE Transactions* 96(2):820-829.

Xu Peng, Philip Haves, and Mary Ann Piette (LBNL), and James Braun (Purdue). 2004. Peak demand reduction from pre-cooling with zone temperature reset of HVAC in an office. *Proceedings of 2004 ACEEE Summer Study on Energy Efficiency in Buildings*. Pacific Grove, CA. LBNL-55800. 2004.

APPENDIX I BUILDING AUDITS

Introduction

Customers' attitudes to prospective utility demand response programs based on HVAC demanding shifting were investigated through discussions with PG&E and SMUD account representatives. The interviews were used to assess the expected response of owners of individual commercial buildings. The issues identified in this investigation were used to frame different aspects of the rest of the project, for example, the magnitude of zone temperature set-point changes, willingness to change control strategies and economic issues such as implementation costs and payback periods. These interviews were also used to identify a sample of buildings to audit regarding their suitability for pre-cooling, both in terms of their building materials and control system characteristics as well as the willingness and ability of the building staff to implement pre-cooling. The building types considered included public sector offices, department stores, large discount stores, hotels, hospitals and libraries - predominantly owner-occupied buildings. Audits were performed in eight large commercial buildings using the procedure described below and the results are presented in Appendix II.

These buildings were assessed for two distinct but related purposes:

- Approximate estimation of the fraction of California buildings that are technically suitable for demand-shifting programs
- Identification of a second candidate test/demonstration site in addition to the Santa Rosa Federal Building

An audit template was developed to evaluate the feasibility of demand shifting with building mass. The audit focused on determining the suitability of the control systems in the buildings for implementing demand-shifting strategies and the robustness of the comfort control. The key issues with regard to the controls are:

- Is it easy/difficult/impossible to reset the zone temperature set-points with a global command?
- If it is difficult or impossible to reset zone temperatures, would it be easy/difficult/impossible to implement a demand-shifting strategy at the air handling unit or central plant level?
- Is the control system functioning correctly or are there problems that would make implementation of any DR strategy problematical?

A closely related issue is how well the building is able to maintain control of comfort. One aim was to find buildings that were well maintained and operating properly, since they would be good candidates for demonstration sites. McCuen Center One was chosen because of its low temperature complaint rate and record of few corrective maintenance events per year.

Audit results

During the discussion with utility representatives, two drivers that were identified for setting up a pre-cooling program from a utilities' perspective are economic incentive and improving public image. The economic incentives for the utility arise from the volatility of the wholesale electricity market, which can produce peak prices that are much higher than the retail prices charged to customers. Beside the economic reasons, setting up pre-cooling programs may also be helpful in improving the public image of a utility company.

However, there are a number of significant barriers to setting up such programs. Most significantly, the expected market response is unclear. Who will participate, and what conditions and incentive structures will induce building owners to participate is unpredictable at present. In addition, building owners will not participate if they believe that pre-cooling will negatively impact occupant productivity – employee costs are far greater than building operation costs. Technically, utility companies are also not sure about the magnitude and the consistency of the load shifting that is obtainable in buildings using demand-shifting strategies.

The buildings that were audited are listed in the Table A1.1. A range of commercial buildings types and functionalities was included in an attempt to determine the prospects for implementation of demand-shifting for the large commercial building market as a whole.

Table A1.1 Buildings Audited

	Building type	District
California EPA	Office, public owner and public tenants	SMUD
SMUD distribution service Sunrise Marriott	Office, private owner, private tenants	SMUD
McCuen Center One (tenant is Sacramento County)	Office, Private owner and public tenants	SMUD
Shriners Hospital for Children	Hospital	SMUD
Apple computer, Sacramento	High tech	SMUD
Kaiser, Oakland	Hospital and office	PG&E
Shorenstein Property	Office, private owner with private tenants	PG&E
Sonoma State University campus	University	PG&E

A template was developed for the audits. The template covers the following area in order to generate a clear picture of the characteristic of the building and its mechanical systems.

- Building characteristics
- Building functions
- Management structure
- HVAC systems
- Control systems

- Building operators
- Utility tariff

The detailed audit results for each building are attached in Appendix II. Key conclusions of the audit regarding the implementation of demand shifting are highlighted below.

Most of the buildings have a fair amount of accessible thermal mass. Thermal mass is concentrated in furniture, documents, and slabs in the buildings. The most common slab type is metal deck with 4" to 6" of concrete, which offers a fair amount of structural thermal mass. By contrast, there is little thermal mass in the walls except in one building (Apple Computer) which was designed for use as a factory. The wall thermal mass is small not only because of the large windows but also because the wall insulation and decorative panels limit the heat transfer. It is also found that, except for the high tech building, most of these buildings have moderate internal loads. The typical office internal load is about 1 W/ft² for lighting and 1 W/ft² for equipment in these buildings.

Offices and schools are potentially good candidates for demand shifting because of their fixed operation schedule. Most office buildings operate from 6 am to 6 pm, except for the high tech building where programmers need 24 hours access to the work areas. It may be more difficult to implement demand-shifting strategies in Hospitals and hotels because of their 24-hour operating schedules and their stricter temperature requirements.

It may be easier to implement demand-shifting strategies in buildings with single owner/tenants because there is less complicated decision-making in these buildings. It was also found that public sector buildings are easier than private owned buildings because public owners are more conscious of their civic responsibilities and also tend to be more innovative and less risk averse.

All of the building operators claimed that they have very sensitive occupants. In hospitals, the temperature control requirements are more stringent than for offices and schools.

Most buildings in the survey have built-up HVAC systems. Most of the control systems in these buildings have DDC control at the zone level, which makes it possible to change zone air temperature set-points globally. Only one building has pneumatic control at the zone level, which make it much harder to change temperature set points globally. Some of these buildings have global temperature reset programmed in already but hardly ever used. For others, it is programmable either in house or by contractors.

Most of the building operators had a negative attitude toward pre-cooling. However, it was not because they had tried it and experienced problems, but because they do not want to take the risk, given the current modest level of incentives.

Regarding the utility tariff, there is only a small incentive because the difference between on-peak rate and the off-peak rate is not very big.

Conclusions

In general, the results of the building audits indicate good demand-shifting potential in large office buildings. The technical barriers for implementing demand-shifting strategies are relatively modest. The characteristics of the building envelopes, the mechanical systems and the control system make most of these commercial buildings feasible for implementing demand-shifting strategies. By contrast, lack of knowledge, resources and incentives for both building owners and building operators are the main barriers.

Appendix IIa. Apple computer

General Information	
Building Owner	Apple computer, Sacramento
Total square footage	10,000 (Data center), 120,000 (office)
Number of floors	2
Location	South Sacramento
Orientation	
Shape	Rectangular
Age	Built in 1991
Function	Designed as manufacture line, now used as office.
Schedule	
HVAC operating schedule	24 hours, 7 days/week.
Occupancy schedule	24/7.
Building envelope	
Wall material,	8 in concrete
Wall R value	R13-19
Wall thickness, or C	
Roof material, R	R5
Floor material	8 in concrete
Floor thickness, or C	
Window glazing	
U and SHGC	No windows
Window to wall ratio	
Internal shading	
Exterior shade, overhung, buildings and trees	
Space	
Number of occupants	800
Equipment load density	Regular office
Lighting density	Designed as 3W/ ft ² , now 1 W/ft ²
Temperature set point	70°F 24 hours
Furniture density	Cubicle, few books and documents
HVAC	
Type of air distribution system	Package units, 25 in total, 7.5-15 tons
Type of terminal units	VAV boxes, VAT, with hot water reheat
Other zone equipment	None
Cooling plant	
Chiller, type, tons	
Water loops and pumps	
Economizer	Yes
Control and monitoring system	
Control vendor, contractor, year	ALC, Webctrl 2.0
Global temperature reset	Present but never used, constant set-point
DDC/pneumatic	DDC
Remote access	Yes, but never been used
Sub meters	No
Operation	
Existing problems	Few

Average cold and hot calls per month	
Balance problems	
Comfort problems	Too warm because of the new 78°F rule
Commissioning history	Commissioned in 2003, operator stated that it was not helpful
Knowledge	
Knowledge of building operator	Very good
How confident to reprogram the controls	good
How confident to change temperature settings	Bad, operator stated that he tried before, got lots of complaints
Utility	
Tariff	Medium Commercial GUS M1
Summer monthly bill	\$70k per month
Electricity end-use breakdown	
Demand charge	Super peak demand \$5.5/ kW/month
Energy charge	Off peak \$0.07/kWh, on peak \$0.095/kWh, super peak \$0.1429/kWh
Pre-cooling	
Difficulty of modifying control system	
Economic incentives for reducing peak demand	Low,
Comfort sensitivity	Very high, operator claim it is the culture of the building
Willingness to conduct test	High
Decision maker	Tracy Pasly
Reasons for implementing pre-cooling or not implementing pre-cooling	Tried before, the temperature rise is about 1°F in 10 minutes, possibly because of the high internal load. Got lots of complaints
Others notes	

Appendix IIb. California EPA

General Information	
Building Owner	California EPA, Owner is City of Sacramento, State is the tenant, Thomas Properties Group manage the building
Total square footage	875,000
Number of floors	
Location	Sacramento downtown, 1001 I street
Orientation	
Shape	
Age	Built in 2000
Function	Office (one floor is computer room 4,000ft ²)
Schedule	
HVAC operating schedule	6 am – 6 pm
Occupancy schedule	8 am – 6 pm
Building envelope	
Wall material,	4 in concrete, no insulation
Wall R value	
Wall thickness, or C	
Roof material, R	
Floor material	4 in light weight concrete, metal deck
Floor thickness, or C	
Window glazing	
U and SHGC	Low E window, single glazing
Window to wall ratio	100% on north façade, 66% on south
Internal shading	
Exterior shade, overhung, buildings and trees	Blind South side has 2ft overhang, nothing on north facade
Space	
Number of occupants	3000
Equipment load density	Regular office
Lighting density	Regular office
Temperature set point	78°F thought out the summer (new regulation by governor)
Furniture density	Regular office
HVAC	
Type of air distribution system	Single duct VAV, 2-3 AHU per floor
Type of terminal units	Fan powered box with electrical reheat
Other zone equipment	None
Cooling plant	
Chiller, type, tons	
Water loops and pumps	
Economizer	Waterside economizer, using chiller as heat exchanger by pumping refrigerant through. The small chiller is on all the time for the computer room. Airside economizer for computer room is not big enough to handle the load, because of the duct is too small.
Control and monitoring system	
Control vendor, contractor, year	Johnson Controls, Metasys
Global temperature reset	Not now, but can be programmed either in house or by the Johnson Controls contractor
DDC/pneumatic	DDC

Remote access	Yes, but never been used
Sub meters	Yes, on each chiller. Fan power is metered by floor
Operation	
Existing problems	Few
Average cold and hot calls per month	
Balance problems	
Comfort problems	Too warm because of the new 78°F rule
Commissioning history	
Knowledge	
Knowledge of building operator	Very good
How confident to reprogram the controls	Good
How confident to change temperature settings	Very good
Utility	
Tariff	Medium Commercial GUS M1
Summer monthly bill	100K per month
Electricity end-use breakdown	
Demand charge	Super peak demand \$5.5/ kW,
Energy charge	Off peak \$0.07/kWh, on peak \$0.095/kWh, supper peak \$0.1429/kWh
Pre-cooling	
Difficulty of modifying control system	Currently they are staging up AHUs at one hour before 6 am
Economic incentives for reducing peak demand	High
Comfort sensitivity	Low
Willingness to conduct test	High
Decision maker	Tracy Pasly
Reasons for implementing pre-cooling or not implementing pre-cooling	<ol style="list-style-type: none"> 1) to save money and improve public image 2) need to test the building before fully implement pre-cooling
Others notes	

Appendix IIc. Kaiser foundation

General Information	
Building Owner	Kaiser foundation health plan, inc
Total square footage	400,000
Number of floors	20
Location	1950 Franklin street
Orientation	West and east sides have glazing, north and south sides have wall only.
Shape	square
Age	Built in 1972
Function	Office, administration
Schedule	
HVAC operating schedule	Depends on the weather, HVAC started 6 hours to 3 hours in advance, which indicates heavy mass
Occupancy schedule	6 am –6 pm
Building envelope	
Wall material,	6 in concrete
Wall R value	
Wall thickness, or C	
Roof material, R	
Floor material	4in slab with steel deck
Floor thickness, or C	
Window glazing	
U and SHGC	Tinted, single glazing
Window to wall ratio	50% on west and east side, 0 on south and north sides, 9 ft ceiling, 2.5 ft plenum
Internal shading	
	Blind
Exterior shade, overhung, buildings and trees	Recessed windows
Space	
Number of occupants	1600
Equipment load density	Regular office
Lighting density	T8
Temperature set point	73°F in summer
Furniture density	Regular with lots of documents and files, server room with dedicated AC
HVAC	
Type of air distribution system	Single duct VAV diffuser with induction units
Type of terminal units	
Other zone equipment	None
Cooling plant	
Chiller, type, tons	Two 490 tons chillers, however just need one
Water loops and pumps	
Economizer	Only in perimeter zones
Control and monitoring system	
Control vendor, contractor, year	2007 new system will be installed. Now Andover system
Global temperature reset	None,
DDC/pneumatic	Pneumatic system, DDC in cooling plant and AHU
Remote access	Yes

Sub meters	Yes, but never been used
Operation	
Existing problems	Complaints from conference rooms. Operator stated that is very hard to control them
Average cold and hot calls per month	1 call per day in average
Balance problems	None
Comfort problems	
Commissioning history	
Knowledge	
Knowledge of building operator	Good
How confident to reprogram the controls	Good
How confident to change temperature settings	Low, risk of complaints
Utility	Not sure
Tariff	
Summer monthly bill	\$800,000 per year
Electricity end-use breakdown	
Demand charge	
Energy charge	
Pre-cooling	
Difficulty of modifying control system	
Economic incentives for reducing peak demand	
Comfort sensitivity	Powerful people in perimeter zones, hard to deal with
Willingness to conduct test	
Decision maker	Chief engineer
Reasons for implementing pre-cooling or not implementing pre-cooling	They cannot because they cannot change the zone temperature set points. It is not a system with DDC to the zones.
Others notes	

Appendix IId Sunrise Marriott, Rancho Cordova

General Information	
Building Owner	Marriott,
Total square footage	195,102
Number of floors	12 (Guest room), 2 (common area)
Location	11211 Point East Drive, Mather Field(Rancho Cordova)
Orientation	Tower windows faces west and east
Shape	
Age	Built in 1986
Function	Hotel
Schedule	
HVAC operating schedule	Guest room and conference based on occupancy schedules Lobby 24 hours
Occupancy schedule	HVAC is default as unoccupied for each room. 80% of guest rooms were occupied most of the time
Building envelope	
Wall material,	Slab walls, concrete
Wall R value	No insulation
Wall thickness, or C	4 in
Roof material, R	R30 insulation
Floor material	4 in concrete
Floor thickness, or C	4 in
Window glazing	
U and SHGC	Single pane, tinted glass
Window to wall ratio	0.3
Internal shading	
Exterior shade, overhung, buildings and trees	Yes
	No
Space	
Number of occupants	About 200 for guest rooms
Equipment load density	Common
Lighting density	Common
Temperature set point	68°F everywhere
Furniture density	Regular
HVAC	
Type of air distribution system	Guest rooms: water source heat pumps, 300 cfm per room, 10% outside air. Air coil cooling tower. Conference room and lobby: air cooled rooftop DX single zone unit, constant volume, electric reheat, each unit is about 7.5-12 tons
Type of terminal units	N/A
Other zone equipment	N/A
Cooling plant	
Chiller, type, tons	N/A
Water loops and pumps	N/A
Economizer	Yes. Recent retrofitted

Control and monitoring system	
Control vendor, contractor, year	TAC control.
Global temperature reset	No. Currently installing 2 way wireless space heat pump remote communication. Both fans and temperature thermostat can be controlled from front desk. The control contractor is using Trace to simulate building and justify savings.
DDC/pneumatic	DDC for conference rooms and common areas
Remote access	Yes
Sub meters	No
Operation	
Existing problems	Few
Average cold and hot calls per month	few
Balance problems	No
Comfort problems	No
Commissioning history	None
Knowledge	
Knowledge of building operator	Very good
How confident to reprogram the controls	Can be done in house or by contractors
How confident to change temperature settings	The temperature can be lowered to as much as 65 oF in both conference and guest room area
Utility	
Tariff	
Summer monthly bill	\$30K per month, 350,000 kWh per month
Electricity end-use breakdown	Unavailable
Demand charge	4K per month in summer, varies by month
Energy charge	Off peak \$0.071/kWh, on peak \$0.095/kWh, super peak \$0.143/kWh.
Pre-cooling	
Difficulty of modifying control system	few
Economic incentives for reducing peak demand	Big incentives because of the demand charge
Comfort sensitivity	Very sensitive, especially if the temperature is too high in summer
Willingness to conduct test	Good
Decision maker	Ron Cain, building manager
Reasons for implementing pre-cooling or not implementing pre-cooling	Very hard to implement pre-cooling because both guest room and conference rooms are operated based on schedule. In Guest rooms, it is impossible to pre-cool the room in night or earlier morning because the guest is in room. For conference rooms, it is hard to pre-cool because they are only occupied less than two days per week.
Others notes	

Appendix IIe McCuen Center One, Rancho Cordova

General Information	
Building Owner	Shiva Inc is the owner, McCuen Properties manages the building, Sacramento County is the tenant
Total square footage	85,000
Number of floors	
Location	10545 Armstrong Ave, Mather Field (Rancho Cordova)
Orientation	
Shape	
Age	Built in 2001
Function	Office
Schedule	
HVAC operating schedule	6 am – 6 pm
Occupancy schedule	6-8 am – 6 pm
Building envelope	
Wall material,	8 in concrete, no insulation
Wall R value	
Wall thickness, or C	
Roof material, R	R-30
Floor material	4 in light weight concrete, metal deck
Floor thickness, or C	
Window glazing	
	Single glazing with slight green tint
U and SHGC	
Window to wall ratio	50%
Internal shading	
	Blind
Exterior shade, overhung, buildings and trees	None
Space	
Number of occupants	125 on first floor and 185 on second floor
Equipment load density	Regular office
Lighting density	0.6 W/ft ² first floor, 0.3 w/ft ² second floor
Temperature set point	The maximum is 78°F because of the contract agreement. The real set-point is unclear
Furniture density	Regular office
HVAC	
Type of air distribution system	Package rooftop unit
Type of terminal units	VAV
Other zone equipment	
Cooling plant	
Chiller, type, tons	
Water loops and pumps	
Economizer	Airside economizer
Control and monitoring system	
Control vendor, contractor, year	Automated Logic Control. Summit Air is responsible for the building controls.
Global temperature reset	Yes. Local set point can be varied within 1 degree by tenants
DDC/pneumatic	DDC
Remote access	Yes
Sub meters	No, only whole building power

Operation	
Existing problems	Little
Average cold and hot calls per month	N/A
Balance problems	N/A
Comfort problems	None
Commissioning history	N/A
Knowledge	
Knowledge of building operator	There is no building operator, summit air has the contract with Shiva Inc for both control and replacing filters
How confident to reprogram the controls	Summit air should be able to do it
How confident to change temperature settings	Good
Utility	
Tariff	Small Commercial GUS S
Summer monthly bill	16K per month
Electricity end-use breakdown	
Demand charge	Super peak demand \$6/ kW,
Energy charge	Off peak \$0.07/kWh, on peak \$0.095/kWh, supper peak \$0.1429/kWh
Pre-cooling	
Difficulty of modifying control system	Summit air need to be paid for reprogram the control
Economic incentives for reducing peak demand	High
Comfort sensitivity	Medium
Willingness to conduct test	High, very enthusiastic to participate the tests
Decision maker	Linda and Mary Leonld
Reasons for implementing pre-cooling or not implementing pre-cooling	3) To save money 4) Maintain comfort
Others notes	

Appendix III Shorenstein Properties

General Information	
Building Owner	Shorenstein Properties
Total square footage	500,000 ft ²
Number of floors	25
Location	1111 Broadway, Oakland
Orientation	Rectangular
Shape	
Age	15 years
Function	Office, with restaurant in the lobby, multi-tenants, mostly bankers, lawyers.
Schedule	
HVAC operating schedule	7 am –6 pm, HVAC started at 6 am
Occupancy schedule	8 am –6 pm
Building envelope	
Wall material,	Window curtain
Wall R value	
Wall thickness, or C	
Roof material, R	
Floor material	3 in slab
Floor thickness, or C	
Window glazing	
U and SHGC	3mm, reflective silver window
Window to wall ratio	100%
Internal shading	
Blind	
Exterior shade, overhung, buildings and trees	No
Space	
Number of occupants	2000
Equipment load density	Regular office
Lighting density	T8
Temperature set point	72- 74°F
Furniture density	Regular, server room with dedicated AC
HVAC	
Type of air distribution system	Single duct VAV with Plenum return
Type of terminal units	Hot water DDC
Other zone equipment	None
Cooling plant	
Chiller, type, tons	York 450 and 900 tons chillers, water cooled. 450 ton chiller has VFD on compressor
Water loops and pumps	2 Cooling tower with VFD fans
Economizer	
Control and monitoring system	
Control vendor, contractor, year	Siemens Apogee
Global temperature reset	Yes
DDC/pneumatic	DDC
Remote access	Yes
Sub meters	None

Operation	
Existing problems	Little
Average cold and hot calls per month	
Balance problems	
Comfort problems	
Commissioning history	Never
Knowledge	
Knowledge of building operator	New operator, experienced
How confident to reprogram the controls	No in house capability
How confident to change temperature settings	Low, risk of complaints
Utility	
Tariff	GNR1 Small commercial building (Gas)
Summer monthly bill	
Electricity end-use breakdown	
Demand charge	
Energy charge	
Pre-cooling	
Difficulty of modifying control system	
Economic incentives for reducing peak demand	
Comfort sensitivity	
Willingness to conduct test	
Decision maker	Owner
Reasons for implementing pre-cooling or not implementing pre-cooling	1) Multi –tenants is the largest barrier 2) Tenants got nothing from the cost saving, because the owner covers the utility bill. 3) Demanding tenants, lawyers are especially hard to deal with 4) Operator is risk adverse.
Others notes	Contact information: Paul Belpasso, 510-867 9418. Suite 110, 500 12 th street. Oakland

Shriners Children's Hospital

General Information	
Building Owner	Shriners Children's Hospital
Total square footage	280,000
Number of floors	8
Location	2425 Stockton Blvd, Sacramento, CA, 95817
Orientation	Facing South West
Shape	Quarter Circle Arc
Age	Construction Completed 1996
Function	Hospital and Medical Research Laboratory
Schedule	
HVAC operating schedule	
Occupancy schedule	Various: 25% - 24hr (inpatient); 50% - 10 to 11hrs (office and lab), 25% - 14 to 16 hrs (service.. etc.). (% applied to floor area)
Building envelope	
Wall material,	Precasted concrete and glazing, with internal furring walls.
Wall R value	R 4 to R11
Wall thickness, or C	4 to 5"
Roof material, R	6" slab with aggregate ballast, at least R-19.
Floor material	6" to 8" concrete slab
Floor thickness, or C	
Window glazing	
U and SHGC	Low-e Green (Metallic) Tint, double pane.
Window to wall ratio	~0.5
Internal shading	
	Yes
Exterior shade, overhung, buildings and trees	None
Space	
Number of occupants	~350 people peak daytime; 80 beds w/ ~ 40 to 50 in-patient, about the same out-patient.
Equipment load density	1.1 to 1.4 W/sf (Only two floors of in-patient care; the research Lab is only operating at about 25% right now; the rest of occupancy is regular office type.)
Lighting density	0.7 to 0.9 W/sf
Temperature set point	Pediatric 75 F; Offices 72 F; Some select areas at 85 F.
Furniture density	About double what a normal office building. Lots of paper and documents
HVAC	
Type of air distribution system	VAV, 12 air handling units (3 @ 100% OA), ~ 500 VAV boxes
Type of terminal units	
Other zone equipment	Qty 75 (1 Ton each) water source heat pumps
	Yes
Cooling plant	
Chiller, type, tons	Qty 3 electric centrifugal chillers @ 775 tons; Only runs 1 at a time. When the research Lab gets up to full operation, they may need more than one chiller.
Water loops and pumps	Primary (one per chiller pumps) and Secondary loops; secondary is variable flow
Economizer	Air side economizers on 14 AHUs

Control and monitoring system	
Control vendor, contractor, year	Johnson Controls Metasys, 1996
Global temperature reset	Chiller water resets based on demand (valve position)
DDC/pneumatic	Zone DDC
Remote access	Available, but not used.
Sub meters	Yes
Operation	
Existing problems	
Average cold and hot calls per month	
Balance problems	
Comfort problems	
Commissioning history	
Knowledge	
Knowledge of building operator	Very high energy issues awareness
How confident to reprogram the controls	In house experience available
How confident to change temperature settings	Willing to do more than they have already tried.
Utility	
Tariff	
Summer monthly bill	
Electricity end-use breakdown	
Demand charge	
Energy charge	
Pre-cooling	
Difficulty of modifying control system	
Economic incentives for reducing peak demand	
Comfort sensitivity	
Willingness to conduct test	
Decision maker	
Reasons for implementing pre-cooling or not implementing pre-cooling	
Others notes	Did some pre-cooling already, using nighttime free cooling. His estimate is they were able to save about 1 hour of chiller run time. This is not rigorous strategy that they use regularly. Only did a small amount this last summer, but more the two previous summers.

Appendix IIIh SMUD Distribution Service

General Information	
Building Owner	SMUD
Total square footage	22,000 ft
Number of floors	2 story
Location	Sacramento 59 th
Orientation	Rectangular, long façade facing north and south
Shape	
Age	30 years
Function	Office
Schedule	
HVAC operating schedule	6 am – 6 pm
Occupancy schedule	8 am – 6 pm
Building envelope	
Wall material,	6 in concrete, no insulation
Wall R value	
Wall thickness, or C	
Roof material, R	
Floor material	5 in slab
Floor thickness, or C	
Window glazing	
	Single glazing, with tint
U and SHGC	
Window to wall ratio	25% east/west, 0 for south/north
Internal shading	
	Blind
Exterior shade, overhung, buildings and trees	The first floor is shaded by second floor, 10 feet. Some vertical fins also
Space	
Number of occupants	200
Equipment load density	Regular office
Lighting density	T8, electronic ballast, 1 w/ft ²
Temperature set point	74°F thought out the summer
Furniture density	Lots of documents, books
HVAC	
Type of air distribution system	Dual duct VAV (first) Single duct VAV(second), one system per floor
Type of terminal units	Fan powered VAV with electrical reheat
Other zone equipment	None
Cooling plant	
Chiller, type, tons	Water-cooled chiller, 60 tons. Four compressors.
Water loops and pumps	Cooling tower
Economizer	Yes, with detached mechanical room
Control and monitoring system	
Control vendor, contractor, year	Siemens
Global temperature reset	Yes
DDC/pneumatic	DDC
Remote access	Yes, but never been used
Sub meters	No

Operation	
Existing problems	Secondary floor, some spots are too hot, the cold deck temperature was decreased to 55°F to solve the problem.
Average cold and hot calls per month	
Balance problems	Little
Comfort problems	
Commissioning history	Never commissioned
Knowledge	
Knowledge of building operator	Good
How confident to reprogram the controls	
How confident to change temperature settings	Current set points are 70°F in winter and 76°F in summer. The operators are worried about the large temperature swing.
Utility	
Tariff	Free electricity
Summer monthly bill	N/A
Electricity end-use breakdown	
Demand charge	
Energy charge	
Pre-cooling	
Difficulty of modifying control system	No technical difficulty
Economic incentives for reducing peak demand	Low
Comfort sensitivity	High
Willingness to conduct test	Good
Decision maker	Manager above Doug
Reasons for implementing pre-cooling or not implementing pre-cooling	5) No economic incentives, because the whole sale electricity is very cheap 6) Willing to join the test for improving company's image
Others notes	Doug Norwood (916-732-6623).

Appendix III Comfort Survey Invitation Letter

General survey

Dear Occupants:

Lawrence Berkeley National Lab is using an innovative on-line survey to identify how to improve our facility services.

Your participation is very important. Please visit this web address on or before Wednesday, September 15:

<http://www.cbesurvey.org/survey/dr/sr/gen>

This survey gives you an opportunity to comment on your satisfaction with spatial layout, office furnishings, office temperature, air quality, lighting, acoustic quality, building maintenance, and the building overall. The survey takes less than 15 minutes to complete and is confidential and anonymous. The results will greatly assist us in making this facility work for you.

If you have questions about the survey or experience any technical difficulties, please contact CBE via e-mail at pxu@lbl.gov or by phone at (510) 486 4549. Thank you in advance for your participation.

Short survey

Dear Occupants:

Lawrence Berkeley National Lab is using an innovative on-line survey to evaluate your satisfaction with our building and identify how to improve our facility services.

This survey will take less than 1 minute to complete and it is confidential and anonymous. You will receive the survey request twice a day until [date]. You might not experience any changes of the temperature in your environment during this period. However, we still encourage you to fill out the survey each time right after you receive the e-mail request.

This survey gives you an opportunity to comment on your satisfaction with your thermal comfort. The results will greatly assist us in making this facility work for you.

Your participation is very important. Please visit this web address right now, and each time you receive this e-mail:

<http://www.cbesurvey.org/survey/dr/sr/short>

If you have questions about the survey or experience any technical difficulties, please contact CBE via e-mail at pxu@lbl.gov or by phone at (510) 486 4549.. Thank you in advance for your participation.

Appendix IV Survey Request Letter

Dear Sir or Madam:

Note: Please take the comfort survey only if you are in your office now.

It's time to take our one-minute survey to record your opinions about the current temperature. Please visit this web address as soon as you can:

<http://www.cbesurvey.org/survey/dr/sr/short>

Even if your experience of the current temperature has not changed since the last time you took the survey, it's important that we hear your opinions. Please take the survey only if you are in the building now. If you're not able to take the survey right away, that's okay- just take it as soon as you can.

Thank you!

If you do not wish to receive the e-mail at all, please respond to me and I will remove you from the distribution list.

Peng Xu

Perceived-Productivity in an Office Building during a Load-Shifting Test

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ABSTRACT

This paper reports on some of the human effects of precooling technology implemented in an office building. The occupants' thermal sensations and work productivity might be affected by the coolth at the beginning of a precooling episode, and by the warmth at the end of the day. These effects have not been studied in an operating building, and would be useful to know in order to optimize building operations. During a brief two-week precooling test in a Sacramento office building, we monitored indoor temperatures and repeatedly surveyed the occupants for their comfort sensation and their perception of how the thermal environment is affecting their work productivity. Significant relationships were found between comfort and productivity, but not between air temperature and productivity. Using a statistical model, we were able to find the borderline temperature when occupants perceived work interference due to coldth. We next related our perceived productivity to actual productivity by adopting an estimate of Wyon and Fisk, and from this were able to quantify the productivity loss/gain caused by the cold portion of this precooling test. The implication for the setpoint temperatures in the environmental control system was discussed.

INTRODUCTION

The potential of on-peak cooling load reduction and energy saving through a precooling technology was explored in an office building in Sacramento. Precooling is a technique used to shift the building's electricity use away from times when the electricity grid experiences peak demand (i.e., making the building 'demand responsive'). Precooling during the night and early morning allows the building to reduce or eliminate its mechanical cooling during the late morning and afternoon. The occupants experience cooler-than-normal air and surface temperatures in the morning and a rising ambient temperature during the afternoon. The occupants' thermal comfort and work productivity might be affected by the coolth at the beginning of the period, and the warmth at the end, and also perhaps by the rate of temperature increase between them [Berglund et. al. 1978]. It would be useful to know these comfort and productivity effects in order to optimize building operations. To our knowledge, they have not been studied in an operating building.

During a brief two-week precooling test in a Sacramento office building, we monitored indoor temperatures and repeatedly surveyed the occupants for their temperature sensation, comfort, and their perception of how the thermal environment is affecting their work productivity. By exploring this data set, we were able to arrive at several conclusions about the comfort and productivity consequences of precooling. Because the test was brief and had a predominance of cool conditions, the main conclusions apply to the cool period in the mornings.

METHODS

Building operation

The test building is located in Sacramento, California, which in summer has a dry Mediterranean climate with a large daily temperature swing. The building was built in 2001 and has a moderate amount of thermal mass in the structure (4 inch concrete floors and 8 inch exterior concrete walls, medium furniture density and commercial carpet on the floors). The total floor area is 85,000 ft² and the window-to-wall ratio is 0.5. Two roof-top air conditioning units serve the building, with direct digital control. From the facilities management records, the building has few comfort complaints, averaging less than 1-2 hot/cold calls per month. There were no reported problems with indoor air quality, and we did not notice any major faults with the mechanical system.

During the baseline test, room air temperature was controlled at 74°F during occupied hours. At night, the mechanical system was shut off and room air temperature was allowed to float. During the load-shed tests, the room air temperature was controlled according to the rules in Table 1, although actual temperatures were found to vary substantially within the building's thermal zones.

Table 1. Precooling zone temperature setpoints and actual range

	Setpoints (°F)	Actual Range (°F)
6AM~12PM	72	(65.6, 76.6)
12PM~6PM	76	(68.3, 81.5)
6PM~6AM	Floating at night	

Temperature measurements

The baseline test was done on 9/24 with the building under normal operation. Load shifting tests were conducted from 9/27~10/5. During this period, the maximal daily outdoor temperatures ranged from 73.4 to 87.8°F, and the minimums ranged from 46.4 to 53.6°F. Indoor temperatures in the vicinity of the occupants were recorded once a minute with small battery-powered data loggers.

Survey

We used a web-based occupant survey to assess occupant thermal sensation/comfort and perceived productivity. This method has been used extensively in thermal comfort research, and in studying the linkage between indoor environment quality and worker productivity in office buildings [Zagreus et. al. 2004]. Although self-evaluation of productivity is necessarily subjective, it presents a useful perspective on productivity in real workplaces. An individual's performance is determined by motivation, expectation, leadership, and other factors besides indoor environmental conditions [Goldman 1994], and perceived-productivity questions help filter those effects. Also, from a company's perspective, worker retention affects long-term productivity, and workers' perceptions of their productivity undoubtedly influence their job satisfaction, so measuring worker-perceived productivity is useful. Finally, there is evidence that perceived-productivity correlates well with performance test in a recent laboratory study [Wittersheh et. al. 2004].

Before the study began, occupants took a background survey that collected basic demographic information such as gender, age, and physical locations in the building, and also their general impressions of indoor environmental conditions in the workplace. This general survey was answered once by each occupant and took about 10 minutes to complete. Then during the study period, occupants took a brief survey twice a day. This repeated survey took less than one minute to complete and contained one question regarding temperature sensation and another regarding perceived productivity. The temperature sensation question employed the Bedford scale, which combines both thermal sensation and thermal comfort within one question. The productivity question was "Does the current temperature in your workspace enhance or interfere with your ability to get your job done?", on a semantic differential scale with color grading from green to background color to red. The survey also invited open-ended comments from occupants. The survey is shown in Figure 1.

occupants were not informed about the precooling program. In a real world application, one would assume that occupants would be notified that precooling might occur during hot weather, that there were public benefits to the program, and suggestions about how to cope with it. Our test subjects' reactions therefore might be stronger than had they been informed of the precooling. Finally, there was a wide range of temperatures within the building. Under the current temperature setpoint policy, we found temperatures spread out among and within individual rooms. Figure 2 shows room and outside air temperatures during a day of the test period. The room temperatures changed from 65.6~71.8°F in the morning to 71.8~81.5°F at the afternoon. There were controllability problems: in one room, the temperature changed up to 4°F/h (from 65.6°F to 81.5°F) during the course of the workday. This added to the range of responses observed.

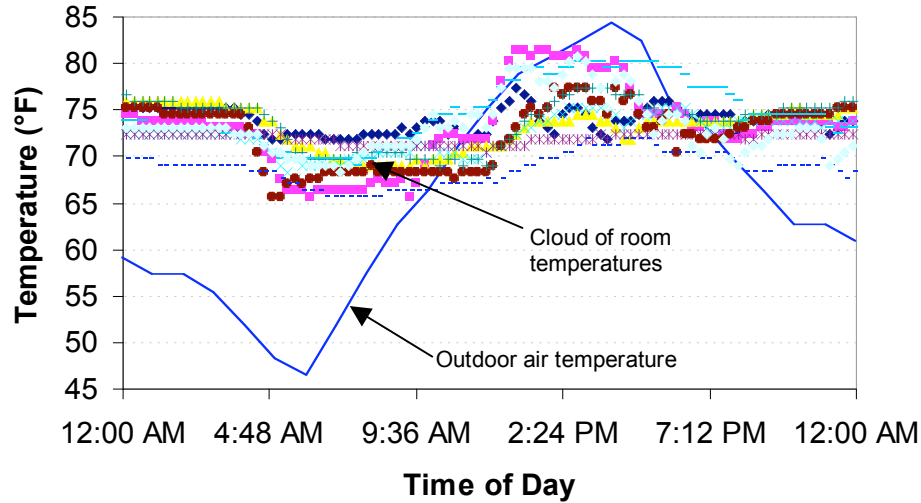


Figure 2 Example room and outside air temperatures

There were approximately 300 occupants in the building. Of these, 77 voluntarily participated in the short survey. The break down is shown in table 2. A total of 1,159 short survey responses were collected, of which 338 could be directly matched with air temperature sensor readings. We used these to form the statistical model.

Table 2. Distribution of the survey participants
Perimeter zone was defined as within 15 ft from an exterior wall

Perimeter zone	Interior zone	
male	18	22
female	15	22

Figure 3 illustrates the distribution of temperature sensation and perceived productivity during the baseline condition and the precooling periods. The horizontal short line in the bar is the median. The bar contains the range between 25th and 75th percentiles. The bracketed whiskers extend to 1.5 times the inter-quartile difference from the 25th and 75th percentiles. [This value is chosen to display data statistics. It has nothing to do with outliers. Analyzing outliers would be a whole story by its own.] The isolated horizontal short lines are outliers. Morning and afternoon are separately considered.

We notice that occupants frequently perceived that they were more productive in the afternoon than in the morning, under both baseline and test conditions. Morning temperatures were cooler than afternoon temperatures in both the baseline and test conditions, in some areas dramatically so (see Figure 2). These too-cool conditions in the morning may negatively influence perceived productivity. However, such a difference in productivity could also be time- and work-pattern-related. For example, occupants may feel more productive after they have been at a task for a longer period.

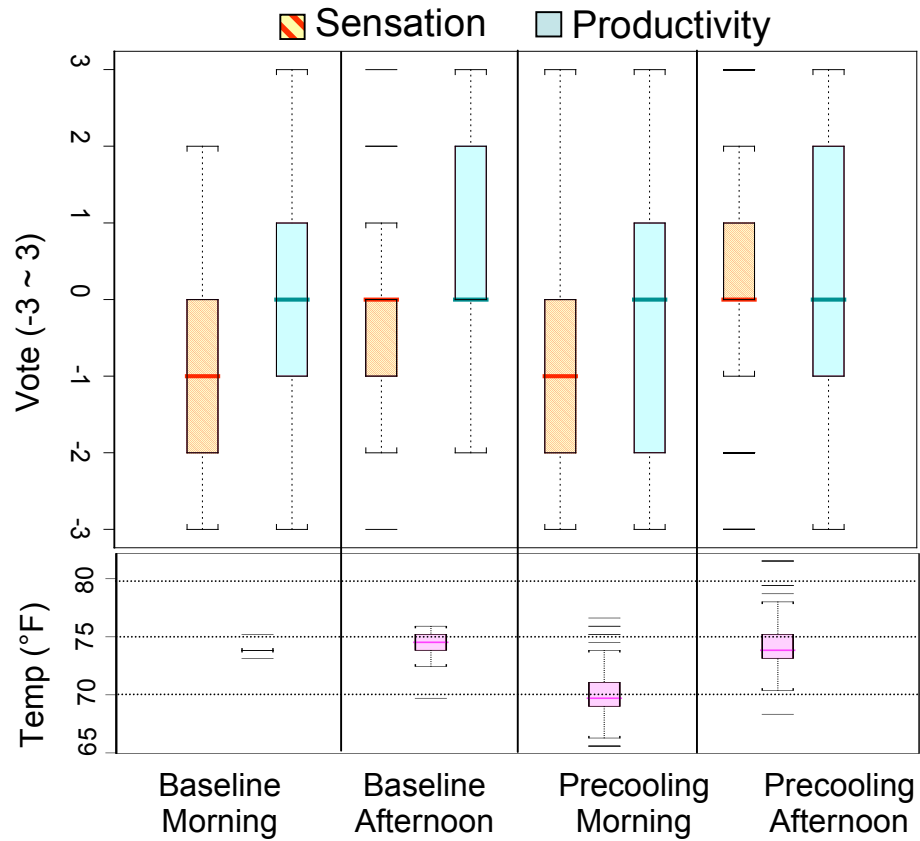


Figure 3. Measurement under precooling and baseline conditions

Figure 4 shows the histogram plot of perceived-productivity clustered according to occupants' temperature sensations. When occupants felt "much too cool" or "much too warm", over 95% voted that the temperature negatively influenced their productivity. When occupants felt "too cool" or "too warm", the negative votes were about 80~85%. When occupants felt "comfortably cool", or "comfortable", they rarely thought their productivity was negatively influenced by temperature. The negative votes counted less than 8%. When they felt "comfortably warm", the negative votes were around 20%. The high number of neutral votes in the comfortable range suggests that when occupants weren't distracted by discomfort, they tended to disconnect their productivity with their thermal sensations.

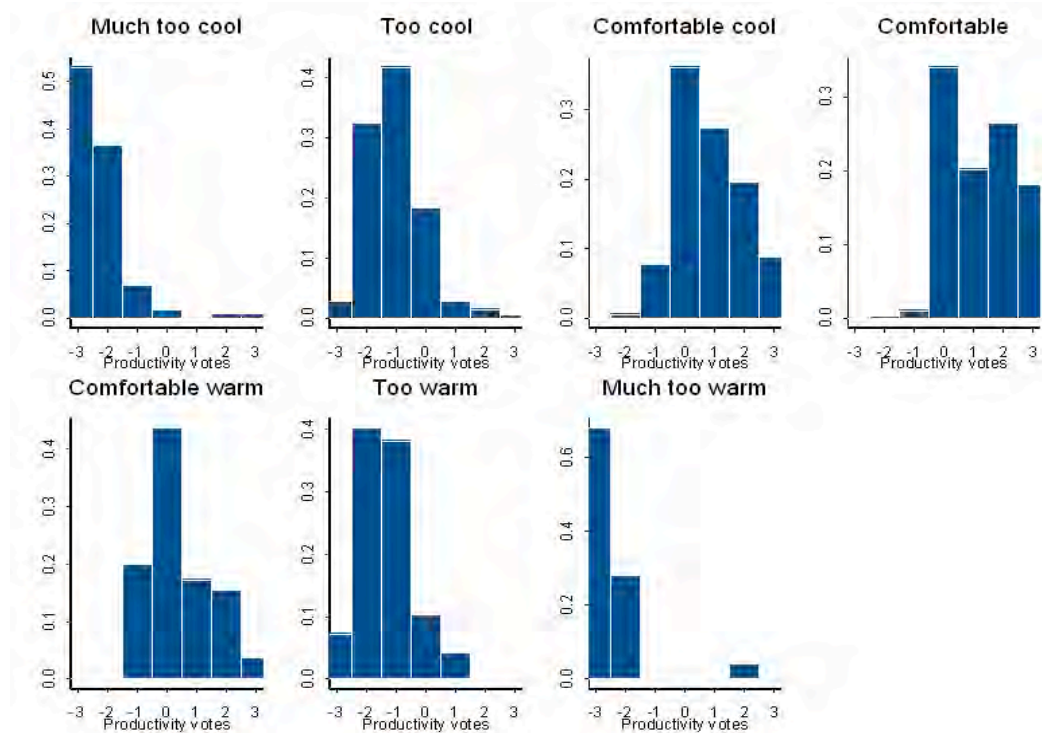


Figure 4. Histogram plot of productivity votes clustered according to sensations

RESULTS

Figure 5~7 are the regression results of the generalized additive model when temperature sensation, measured temperature, and time are explanatory variables in fitting the productivity model. The y-axis indicates the contribution of each explanatory variable on the prediction. The density of hash marks at each point along the x-axis reflect the frequency of votes at each point along the sensation scale. Temperature sensations and perceived productivity has an inverted U shape correlation, as shown in figure 5. The sensation of “comfortable” and “comfortably cool” enhances productivity. “Comfortably warm” does not enhance productivity as does “comfortably cool”. “Too cool/warm”, or “much too cool/warm” interfere with productivity. The more extreme the sensation is, the more negative impact it has on productivity. This is evident outside ASHRAE’s comfort zone.

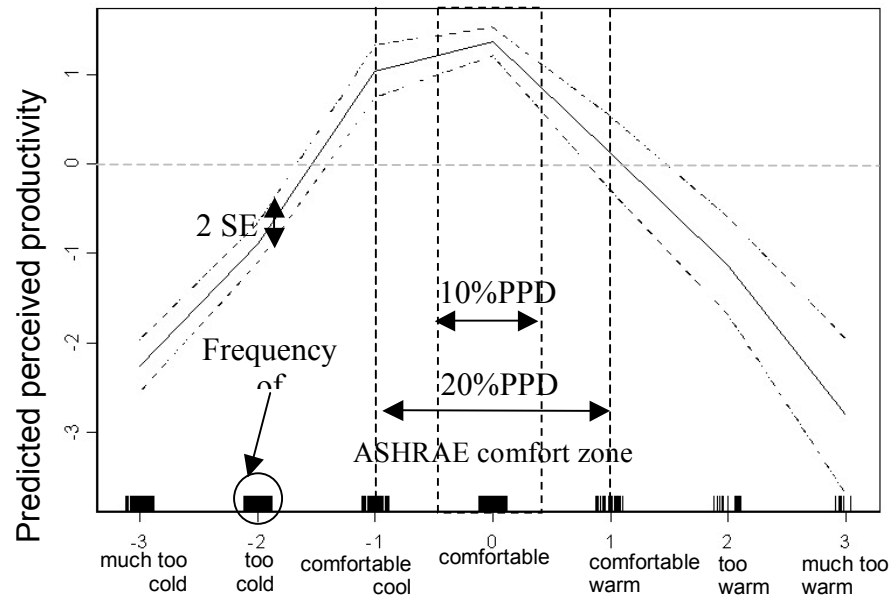


Figure 5. Contribution of temperature sensation to productivity

The impact of measured air temperature on productivity was examined separately from the impact of thermal sensation. Figure 6 shows the correlation between air temperature and productivity. Only when temperature was above 78.7°F, it had negative influence on productivity. However, due to the sparse number of data points at this range, we can not make this conclusion. Moreover, the temperature term is not significant in the model. At first, we thought the sensation term confounded the temperature in this model. We then built a sub-model without sensation term and tested it against the original model. The F-test shows the sub-model is not significant. Less dependence of productivity on temperature than sensation does not conflict with the fact that thermal sensations do have a significant influence, and also it agrees with findings in Federspiel et. al. 2002, MacCartney et. al. 2002, and Pepler et. al. 1968.

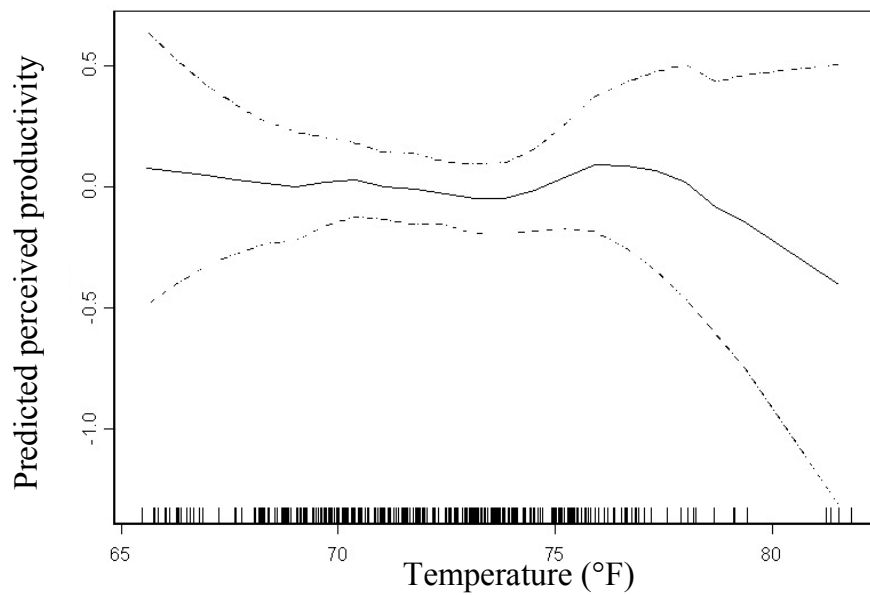


Figure 6. Contribution of temperature to productivity

Figure 7 shows the contribution of the time to productivity. The majority of occupants took the survey when reminded, around 10AM and 2PM. Time was therefore treated as a factor with two levels. “Morning” refers to the time before 11:30AM, and “afternoon” refers to the time after that. There were an equal number of votes at each level. We found that occupants perceived being significantly more productive at the afternoon than in the morning. The difference was 0.2 productivity scale units, about 30% of the influence of one unit of temperature sensation.

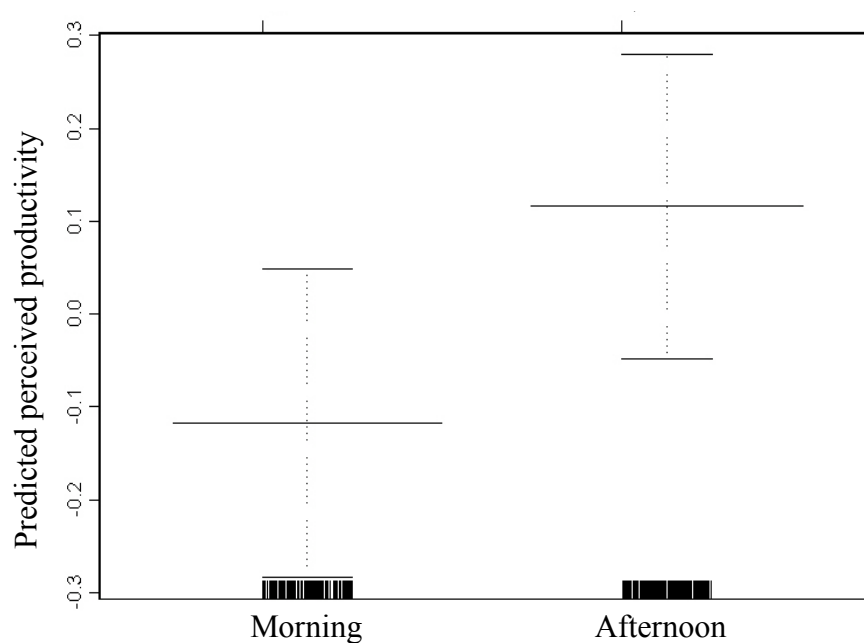


Figure 7 Contribution of time factor to productivity

DISCUSSION

This study shows that occupants' perceived productivity decreases when they feel warmer than thermally neutral. This appears to be in accordance with many actual productivity studies in laboratories and in call centers, including Pepler et al 1968, Meese et al. 1984, Wyon 1974, 1996, Niemela et al. 2002, Federspiel et al. 2002, and Wetterseh et al. 2004].

Our analysis finds that when occupants feel comfortable, their productivity is not negatively influence by temperature. This result is supported by Wyon's (1975) and Fang's (2002) laboratory studies. Both Wyon and Fang's study did not find differences in actual task performance when subjects maintained comfortable conditions, either through adjusting their temperatures, or adjusting their clothing insulation.

Using the statistical model, we calculated the borderline temperature when occupant perceived work interference due to the coldth. This occurs at -1.4 under Bedford's 7 pts scale. This value is outside ASHRAE's comfort zone (20% predicted percent dissatisfaction corresponds to ± 1 PMV values.) Assuming an occupant wears standard summer clothing (0.5clo) and works sited (1.2met activity level), we found the critical temperature at 67.8°F (19.9°C). Our finding is close to the lower end of temperature range where no significant effort was rated in Pepler's study. Pepler et. al. (1968) studied the effect of different room temperatures on students learning efficiency. Room temperature of an environmental chamber was controlled at six different levels, from 16.7, 20.1, 23.4, 26.7, 30, to 33.3°C. He found no significant difference on effort ratings during 20.1~26.7°C. However, cold temperature (16.7°C) significantly increased students' effort ratings.

Another study involve low temperature is Meese et. al.'s factory workers study. Meese et. al. (1984) reported the significant adverse effects of cold on manual dexterity and flexibility in a laboratory test of factory workers. The extent of this adverse effects caused manual performance at 18°C to be 85%~90% of that at 24°C, when the majority voted comfortable. Since most office works involve extensive movements of hands and fingers, it is possible that reduced manual dexterity and flexibility at low temperature partially causes the loss of perceived productivity.

Determining a quantitative relationship between temperature and actual productivity loss is useful because it can guide environmental system operations to minimize the energy consumption and maximize the occupant productivity in buildings. Therefore, it is useful to connect occupant perceived productivity to some actual measures. We didn't find any previous studies which address this issue. From the survey, we read occupants have wide different opinions when evaluate the degree of influence of temperature on productivity. We thus use some expert assumption to impose a cap to the scale. [Wyon 2004] and [Fisk 2000] discussed the estimated range of thermal influence on worker productivity. Wyon suggests the maximum influence in laboratory is around 9% and higher in real workplaces (Wyon), and Fisk, 2~20%. We assign 3% productivity loss per one unit thermal sensation change and totally change of 18% productivity could be reached (Figure 8). With this assumption, we obtained a slope of 1.7%/°C productivity loss when occupants feel too cold. Figure 9 shows the estimated number in comparison with the previous studies.

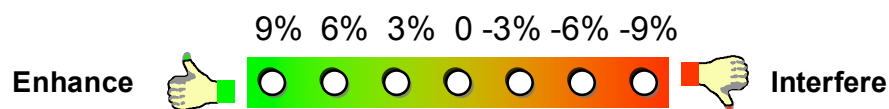


Figure 8 Quantitative interpretation of the 7 pts scale

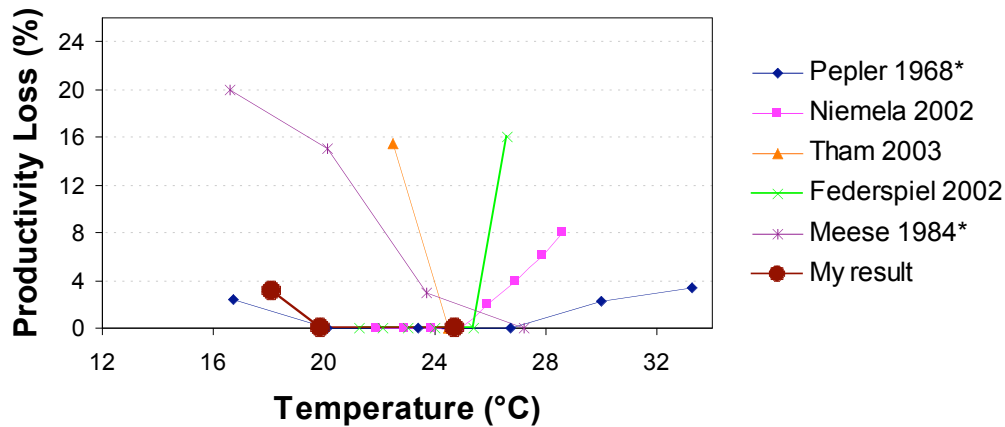


Figure 9 Productivity Loss versus Temperature (* adjusted data such that subjects have the same level of clothing insulation 0.5clo.)

The precooling strategy used in the tests cooled the space in the morning while occupants were present. Occupants were exposed to the cool air and the coolest part of radiant enclosure directly. That increased the risk of cold complaints and caused perceived productivity loss. Perhaps the precooling should have occurred before occupancy, so that the structural mass was cooled to greater depth but with a warmer surface temperature. Temperature setpoints thus may be optimized to improve productivity over that of neutral temperature during occupied off-peak time, and avoid productivity loss during occupied on-peak time.

It is desirable to explore further the effect of the warmth at the end of the day to perceived productivity in future.

CONCLUSION

In conclusion, we found:

1. Temperature sensation (from cold to hot) and perceived-productivity had an inverted U-shaped correlation. Sensations of 'comfortably cool' and 'comfortable' most enhanced productivity. The sensation of "comfortable" and "comfortably cool" enhances productivity. "Comfortably warm" does not enhance productivity as does "comfortable cool". "Too cool/warm" reduces productivity.
2. The borderline temperature when occupant perceived work interference due to the coldth. This occurs at -1.4 under Bedford's 7 pts scale. This value is outside ASHRAE's comfort zone. Assuming an occupant wears standard summer clothing (0.5clo) and works sited (1.2met activity level), the operative temperature is at 67.8°F (19.9°C).
3. Perceived productivity is significantly higher at the afternoon than in the morning, when thermal sensation has been controlled.
4. The precooling strategy may be optimized to improve productivity over that of neutral temperature during occupied off-peak time.

ACKNOWLEDGEMENT

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REFERENCES

- Berglund, L. G. and R. R. Gonzalez (1978). "Application of Acceptable Temperature Drifts to Building Environments as a Mode of Energy Conservation." ASHRAE Transactions 84: 110-121.
- Fanger, P. O. (1972). Thermal Comfort, McGraw-Hill Book Company.
- Fang, L., D. Wyon, et al. (2002). "Sick Building Syndrome Symptoms and Performance in a Field Laboratory Study at Different Levels of Temperature and Humidity". Indoor Air '2002, Monterey, CA, USA.
- Federspiel, C., G Liu, et al. (2002). "Worker Performance and Ventilation: Analysis of Individual Data for Call-Center Workers". Indoor Air 2002, Monterey, CA, USA.
- Fisk, W. J. (2000). "Health and Productivity Gains from Better Indoor Environments and their Relationship with Building Energy Efficiency", Annu. Rev. Energy Environ. 2000. 25:537-66
- Hedge, A. "Linking Environmental Conditions to Productivity", Eastern Ergonomics Conference and Exposition, New York, June, 2004.
- Goldman, R.F. "Productivity in the United States: A Question of Capacity or Motivation", ASHRAE Trans. 1994, Vol.100, Part 2, Paper number OR-94-13-4, 922~933
- McCartney, K. and M. Humphreys (2002). Thermal Comfort and Productivity. Indoor Air '2002, Monterey, CA, USA.
- Morgan, CA. R. de Dear, G. Brager (2002). "Climate, Clothing and Adaptation in the Built Environment", Indoor Air 2002, Monterey, CA, USA.
- Niemela, R., M. Hannula, et al. (2002). "The effect of air temperature on labour productivity in call centres--a case study." Energy and Buildings **34**(8): 759-764.
- Pepler, R. and R. Warner (1968). "Temperature and Learning: An Experimental Study." ASHRAE Trans. 74(2): 211-224.
- Tham, "Effects of Temperature and Outdoor Air Supply Rate on the Performance of Call Center Operators in the Tropics", Indoor Air 2004; 14 (Suppl 7): 119-125
- Wyon, D., P. Fanger, et al. (1975). "The Mental Performance of Subjects Clothed for Comfort at Two Different Air Temperatures." Ergonomics **18**: 359-374.
- Wyon, D., I. Andersen, et al. (1979). "The Effects of Moderate Heat Stress on Mental Performance." Scand J Work Environ Health 5(4): 352-61.
- Wyon, D., I. Wyon, et al. (1996). "Effects of Moderate Heat Stress on Driver Vigilance in a Moving Vehicle." Ergonomics 39(1): 61-75.
- Wyon, D., "the Effects of Indoor Air Quality on Performance and Productivity", Indoor Air 2004; 14 (Suppl 7): 92-101
- Witterseh, T. D. Wyon, et. al., "the Effects of Moderate Heat Stress and Open-plan Office Noise Distraction on SBS Symptoms and on the Performance of Office Work", Indoor Air 2004; 14 (Suppl 8): 30-40
- Zagreus, L., Huizenga, C., E. Arens and D. Lehrer, "Listening to the Occupants: A Web-based Indoor Environmental Quality Survey", Indoor Air 2004; 14 (Suppl 8): pp. 65-74.